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DIVISION OF MINES AND GEOLOGY

MARSHALL T. HUNTTING, Supervisor

Bulletin No. 58

CHEMICAL AND PHYSICAL CONTROLS FOR BASE METAL DEPOSITION IN THE CASCADE RANGE OF WASHINGTON

By

ALAN ROBERT GRANT

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Errata sheet for Washington Division of Mines and Geology Bulletin 58,

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By Alan Robert Grant

Errors noted in the printed text are listed below. The editors regret these and possibly other mistakes in editing.

Page	
12	Paragraph 5, line 2, "heliocpter" should read helicopter.
14	Paragraph 6, line 6, "programed" should read programmed.
15	Figure 2, "Mesoic" in explanation should read Mesozoic.
19	Paragraph 4, line 7, "authochthonous" should read autochthonous.
22	Paragraph 6, line 4, "extension Mesozoic" should read extension of the Mesozoic.
22	Paragraph 7, line 1, "aforemention" should read aforementioned.
25	Paragraph 4, line 7, "Misch" should be changed to Vance.
25	Paragraph 7, line 7, "Tatoosh, pluton" should read Tatoosh pluton.
26	Paragraph 1, line 4, "classical" should read classic.
32	Paragraph 4, line 1, "alkaline" should be changed to acidic intrusive.
33	Paragraph 1, line 1, "alkaline" should be changed to acidic intrusive.
48	Line 3 of Figure 16 caption, "alkaline" should be changed to acidic intrusive.
49	Paragraph 3, line 5, "Creasy" should read Creasey.
51	Paragraph 3, line 1, "Creasy" should read Creasey.
52	Paragraph 5, line 1, "degree atomic" should read degree of atomic.
56.	Paragraph 1, line 1, "Table 1" should read Table 3.
56	Paragraph 3, line 2 , "feldpathi-" should read feldspathi-.
57	Paragraph 1, line 1, "invironment" should read environment.
58	Paragraph 2, line 2, "classical" should read classic.
60	Paragraph 4, line 4, "formation if" should read formation of.
60	Paragraph 6, line 2, "magmatitic" should read magmatic.
68	Paragraph 7, line 4, "silfides" should read sulfides.
71	Last paragraph, line 1, "structural, as" should read structural belt, as.
75	Figure 24, "Pre-Tertiory" in explanation should read Pre-Tertiary.
77	Paragraph 5, line 5, "there there is" should read there is.
79	Last paragraph, item 4, "quartz dioritic" should read quartz diorite.
86	Figure 30, credit for map should be given to Ellis, 1959 and Foster, 1960.
87	Last paragraph, line 1, "complex that that" should read complex than that.
89	Figure 31, credit for map should be given to Felts, 1939 and Heath, 1966.
101	Paragraph 3, line 3, "ingress or egress to the claim site" should read ingress to or egress from the claim site.
103	10th reference, "Bican" should read Bichan.

Errata in the Washington Division of Mines and Geology Bulletin 58,

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15 Figure 2, "[illegible]" in explanation should read [illegible].

19 Paragraph [illegible], line 2, "[illegible]" should read [illegible].

22 Paragraph 6, line 4, "extension Mesozoic" should read extension [illegible].

22 Paragraph 7, line [illegible], "of saturation" should read of [illegible].

25 Paragraph 4, line 7, "[illegible]" should be changed to [illegible].

25 Paragraph 7, line 7, "[illegible] pluton" should read [illegible] pluton.

26 Paragraph 1, line 4, "[illegible]" should read [illegible].

32 Paragraph 4, line 1, "[illegible]" should be changed to [illegible].

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60 Paragraph 4, line 4, "[illegible]" should read [illegible] section of.

60 Paragraph 5, line 6, "[illegible]" should read [illegible].

63 Paragraph 7, line [illegible], "[illegible]" [illegible].

71 Last paragraph, line 1, "[illegible]" should read [illegible].

75 Figure 24, "[illegible]" in explanation should read [illegible].

77 Paragraph 5, line 5, "[illegible]" should read [illegible].

79 Last paragraph, line 4, "quartz [illegible]" should read quartz [illegible].

86 Figure 30, credit for map should be given to [illegible] and [illegible].

87 Last paragraph, line 1, "[illegible] that that" should read [illegible].

89 Figure 31, credit for map should be given to Fritz, 1929 and [illegible], 1965.

101 Paragraph [illegible], line [illegible], [illegible]

103 10th reference, "Bishop" should read Bichon.

FOREWORD

The Cascade Range of Washington has been the scene of mineral exploration and production for at least 115 years, since the first discovery of gold in the State—on the Yakima River—was reported in 1853. Although this discovery apparently was accidental, or at least was incidental to exploration for a railroad route through the Cascades, the search for metallic ores soon was begun seriously and has been continued to the present time.

In the latter part of the 1800's the mountains were "crawling with prospectors," and most of the presently known prospects in the Cascades probably had been discovered before the turn of the century. The early prospectors were moderately successful, and several million dollars' worth of gold and lesser amounts of copper and other metals were produced as a result of their efforts. Essentially all of these discoveries and the resultant production can be credited to the dogged persistence and hard work of the early prospectors; only a modicum of credit can be given to conscious use of geologic principles.

In the 1900's a few mines in the Cascades have had records of production exceeding $1 million each in value; one, the Holden mine in the central part of the North Cascades, produced more than $66 million in copper, gold, silver, and zinc in the 20-year period it operated.

Relatively little has been published on the geology of the very large area that encompasses the Cascade Mountains of Washington, so there has been little opportunity to use geology properly to guide mineral exploration there. The Division of Mines and Geology was fortunate in being able to obtain the services of Alan Robert Grant to continue his already extensive studies of geologic controls for ores in the Cascades and to write this report of his findings published as Division of Mines and Geology Bulletin No. 58. Dr. Grant earned both his M.S. and Ph. D. degrees in geology from the University of Washington, basing his dissertations on studies of the geology of part of the Cascade Mountains. His academic studies, his work for 6 years as exploration geologist for a major mining company, mostly in the Cascades, and subsequent work on this project for the Division, as well as independent investigations as a consultant, have given him an unparalleled opportunity to investigate the geology of these mountains and to discover which geologic features are related to or control the occurrence of metallic ores in the Cascades. This report details the findings and conclusions resulting from his work. It should be helpful to other explorationists in their efforts to find new ore deposits in the Cascades to help meet the nation's ever-increasing demands for metals.

Marshall T. Huntting, Supervisor
Division of Mines and Geology

October 31, 1968

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CHEMICAL AND PHYSICAL CONTROLS FOR BASE METAL DEPOSITION IN THE CASCADE RANGE OF WASHINGTON

By Alan Robert Grant

ABSTRACT

The Cascade Range of Washington can be considered metallogenetically to be primarily a copper province. Structural and chemical data compiled through examination of numerous copper occurrences in the Cascades indicate a marked parallel of physical conditions for sulfide deposition. In their probable order of significance, the environmental criteria are as follows:

(1) Adjacent or subjacent high-level intrusive activity subsequent to regional metamorphism, most commonly in the time span from 15 m.y. to 30 m.y.

(2) Transverse northeast-trending structural belts that obliquely cut the northwest regional trend of the range.

(3) Potassium-silica wall rock alteration. Most important of the silicates in the alteration suite are orthoclase, secondary biotite, and quartz.

(4) The intersection of northwest-trending and northeast-trending structures.

The varying geologic environments in the Washington Cascades present a complex setting for the sulfide deposits. The North Cascades are composed of predominantly pre-Tertiary metamorphic rocks invaded by Tertiary calc-alkaline intrusive rocks. The Central Cascades, lying south of the North Cascades, exhibit a younger, higher level geologic environment composed of predominantly early to middle Tertiary volcanic rocks and subordinate sedimentary rocks that are also intruded by Tertiary calc-alkaline igneous rocks.

Although the Tertiary Cascade intrusions are predominantly quartz dioritic in bulk composition, late-stage magmatic differentiates of quartz monzonite and granite are relatively common. The emplacement of these late intrusive rocks appears to have been partly controlled by transverse structural activity. Sulfide concentrations are considered to be partly dependent on the degree of acidic intrusive activity and the intensity of transverse structural deformation. Potassium-silicate alteration, commonly associated with copper mineralization, appears to be directly related to late-stage magmatic fractional crystallization processes.

Supergene alteration over sulfide zones in the Cascades is shallow or nonexistent. In some areas, however, supergene quartz-sericite alteration and varying limonite development are sufficiently developed to conceal the nature of the underlying sulfide deposit.

INTRODUCTION

Interpretation of presently available geologic data indicates that most of the periods of metal deposition in the Cascade Range of Washington are, at least in part, genetically related to Late Cretaceous-Tertiary intrusive episodes. Chemically, the most favorable environment for sulfide deposition is high in potassium and free silica. Characterizing the advanced stages of these chemical alteration conditions are the mineral assemblages orthoclase and (or) secondary biotite or quartz-sericite. Wall rock alteration includes both deuteric and hydrothermal processes, the intensity of which depends primarily upon the degree of fracturing in the country rock prior to the introduction of secondary material. Broadly speaking, the primary physical controls for the distribution and concentration of sulfides appear to be a series of structural couples involving systems striking both northwest (paralleling regional trends) and northeast.

Successful base-metal exploration in an area such as the Washington Cascades requires a basic understanding of the various geologic factors related to the distribution of the ore deposits. Any geologist contemplating Cascade work should be well grounded in the fundamental concepts of petrology and structure, as these constitute two of his most beneficial aids. The acquisition of the detailed data necessary for this understanding may seem a bit academic, yet in numerous instances it has been demonstrated that a fair economic appraisal of a particular property or mining district depends primarily upon the ability of the geologist to recognize the subtle environmental differences that could lead to the discovery of a major ore deposit.

TOPOGRAPHY AND GLACIATION

The North and Central Cascades (Fig. 1) can be divided into two distinct geographic as well as geologic provinces. The boundary line between these two areas is roughly a diagonal drawn from lat 48° N. on the west side of the range to lat 47°20' N. on the east side.

The North Cascades present a formidable mountain barrier 60 to 70 miles wide. Average peak elevation in the northern range is approximately 8,000 feet. Maximum relief is variable but generally is only slightly less than the average peak elevation. In the Lake Chelan area, for example, the elevation difference between Lake Chelan and Bonanza Peak (situated 10 air miles west of the lake) is approximately 8,500 feet. Bonanza, at 9,511 feet, is the highest nonvolcanic peak in the range. North faces of the higher peaks commonly rise steeply for over a vertical mile from the valley floors. Most valleys were extensively glaciated in Pleistocene time; this action resulted in steep-sided, U-shaped configurations.

According to Dr. S. C. Porter (oral communication, 1967), the Cascade Range of Washington at the present time has approximately 385 sq km of permanent ice fields and glaciers. About 50 percent of this ice occurs on the Pleistocene stratovolcanoes; Mount Rainier has the largest glacial system, occupying an area of 88 sq km. There are approximately 250 sq km of ice in the North Cascades, much of which occurs as glaciers along the north and east flanks of the high peaks of the Pickett Range, the Eldorado group, and the Dome Peak massif. These glaciers are mostly of the hanging variety, but small valley tongues of ice do occur beneath some of the larger masses. Although several of the glacier fronts appear to be slowly advancing, there is corresponding thinning in the upper névé area. Recently deglaciated slabs and end moraines devoid of vegetation indicate a prolonged period of recession. The maximum post-Pleistocene glacial advance in most cases was probably not more than 1 mile downvalley from the present terminus. The local climatic variations that are responsible for these minor fluctuations in glacier flow are now being studied by the Hydrology Branch of the U.S. Geological Survey. In order to facilitate these studies, a permanent camp on the South Cascade Glacier, 8 miles south of Cascade Pass on the Cascade crest, has been established.

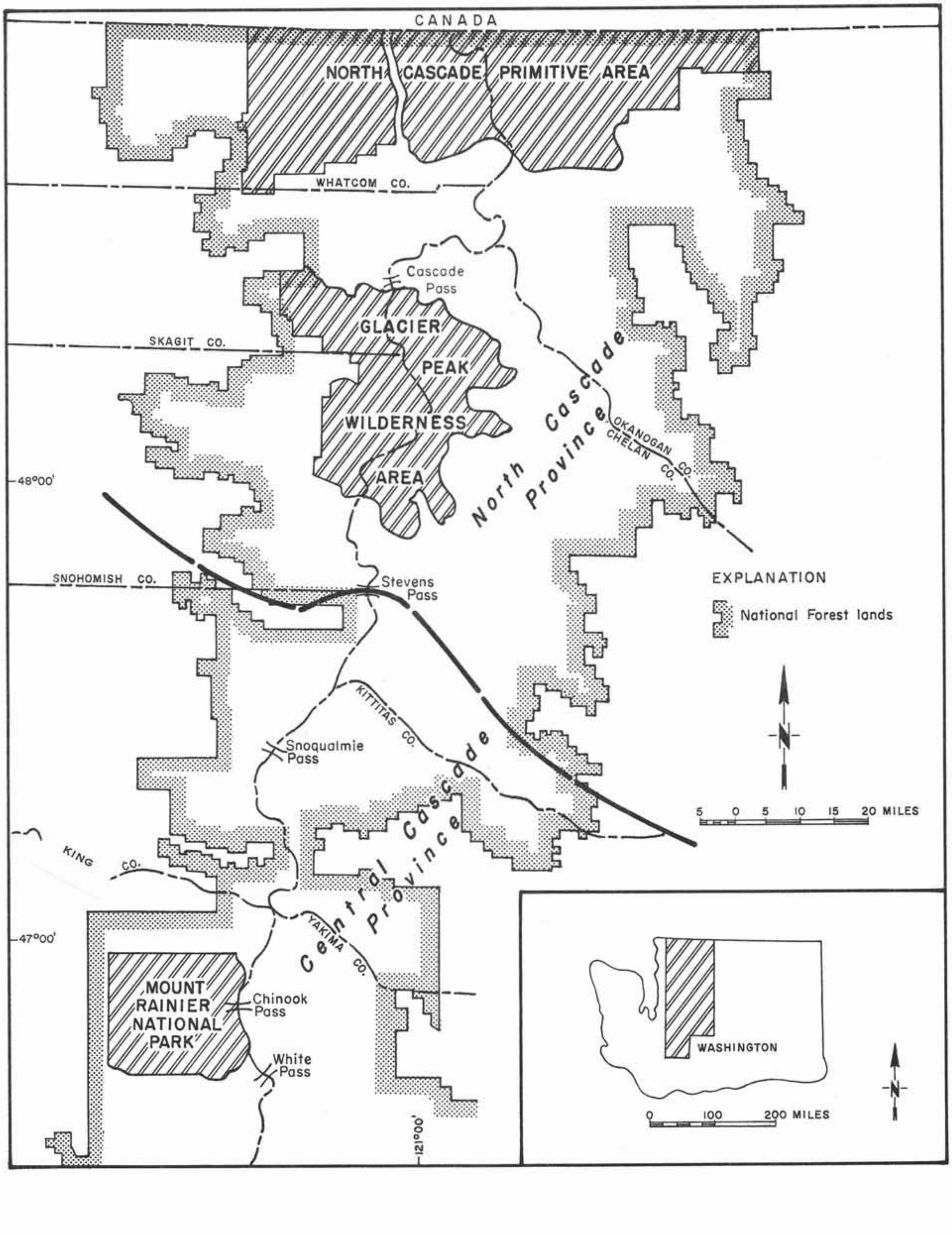

FIGURE 1.—Index map, Cascade area, Washington.

The rugged alpine character of the North Cascades becomes more subdued to the south in the Central Cascades. In contrast with the northern ranges, the Central Cascades contain little permanent ice except on the Pleistocene volcanoes of Mounts Rainier, St. Helens, and Adams, and a few of the high peaks along the Cascade crest. The average peak elevation in the northern part of the Central Cascades is about 6,000 feet, and decreases to approximately 3,500 feet at the southern end of the province. South of White Pass, few peaks reach timberline.

ACCESS

Four cross-mountain highways (over White, Chinook, Snoqualmie, and Stevens Passes) facilitate vehicular access. The northernmost of these highways, at Stevens Pass, is situated along the boundary between the Central and North Cascades. A fifth cross mountain highway, the North Cascades Cross-State Highway, is currently under construction; its estimated completion date is some time in 1969. This new road, crossing the range at approximately lat 48°30' N., will greatly improve access to the northern mountains.

Despite these highways and numerous secondary forest roads, access to most of the mountain areas is difficult. In the North Cascades, logging roads abound along the west and east flanks of the range. The center of the range is relatively isolated, and entrance into most areas requires long arduous trips along brush-filled valleys and up steep, timbered hillsides. Above timberline, high-level cross-country travel commonly requires mountaineering experience.

The Central Cascades retains much of the rugged character found farther north. In general, however, there are more numerous logging roads and forest trails. In the southern part of the Central Cascades, forest access roads abound. The country is brushy, but overall access problems are considerably eased.

In much of the northern section of the range, the most efficient means of access is via helicopter. This method, of course, is relatively expensive, but experience has shown that one heliocpter day is equivalent to a minimum of one week in the bush without aerial support. Anyone contemplating helicopter operations in the North Cascades should check in advance with Federal agencies charged with land administration in the range to ascertain which areas are closed to helicopter operations or are open under special use permit only.

PREVIOUS INVESTIGATIONS

With a few notable exceptions, useful literature on Cascade ore deposits is wanting. References about various mining prospects and districts are numerous, but few are of value to the economic geologist. However, a few early papers are worthwhile. These include Spurr's (1901) work on the Monte Cristo ore deposits, Weaver's (1912) work in the Index area, and Patty's (1921) discussion of the metal mines in Washington.

Coupled with renewed interest in exploration of the range, a series of more significant contributions to our Cascade knowledge has been presented over the past two decades. Carithers and Guard (1945) discussed the geology and ore deposits of the Sultan Basin area. Youngberg and Wilson (1952) described the geologic framework of the Holden mine. Purdy (1954) summarized the molybdenite occurrences in Washington. Later, Huntting (1956) presented an inventory of the known metallic mineral occurrences in the State. The U.S. Geological Survey (1966) in cooperation with other agencies published a report on the geology and mineral resources.

More important than the papers on economic geology has been the coverage of fundamental geologic mapping in the range. The early workers include Russell (1900) and Smith and Calkins (1904), who made reconnaissance traverses in the Skagit country, and Daly (1912), who mapped along the 49th parallel. Farther south, Smith (1903b, 1904) mapped the Ellensburg and Mount Stuart quadrangles. A little later, Smith and Calkins (1906) studied the Snoqualmie Pass area.

Apart from these studies, little serious geologic work was undertaken in the Cascades until the post-World War II period. In the North Cascades, Dr. Peter Misch, of the University of Washington, began an investigation of the northernmost part of the range in 1949. Commencing in the early 1950's, Dr. Misch and some of his graduate students began a systematic study as part of a project to map the geology of the North Cascades. The initial phase of this project (reconnaissance mapping) is now nearing completion. In addition to the University of Washington activities, the U.S. Geological Survey also has mapped 3 quadrangles in the Lake Chelan area. On the eastern flank of the Northern Cascades, in the Methow Valley, Barksdale (1948, 1958, 1960 and continuing) has been studying the complex Cretaceous section.

In the Central Cascades, as in the North Cascades, much of the reconnaissance mapping has been accomplished by University of Washington graduate students. In this area many of the students were guided by Dr. H. A. Coombs. Other recent workers, too numerous to mention here, also have contributed to our knowledge.

All in all, collective geologic knowledge of the Cascade Range of Washington is reasonably complete from a reconnaissance standpoint. More detailed and sophisticated studies are underway, but the initial basic data, as now available, are invaluable as a foundation for the interpretation of the Cascade ore deposit environments.

PURPOSE OF THE STUDY

The Cascade Range of Washington has been the scene of a considerable amount of prospecting and exploration activity since the late 1800's. As was also the case in many other areas of the western United States, serious geologic study followed much later than the initial and sometimes most thorough stage of amateur prospecting. This acquisition of basic data concerning the areal geologic environments, coupled with changing market conditions and improved mining techniques, has necessitated a continuous re-evaluation of many older mining districts and, in some instances, the establishment of new target areas for exploration and development.

In recent years the Washington Cascades have experienced a revitalization of exploration activity. The future holds a promise of even greater efforts. Anticipating this interest, I have spent several years attempting to integrate the ever-improving and expanding geologic coverage of the range with a study of the ore deposit environments. It appears now that the available data are sufficient to present a series of hypotheses equating geologic evolution of the Cascades with base metal distribution. This paper comprises only what may be considered an initial progress report on the subject, and it is hoped that other Cascade workers will continue, on a more fundamental level, those studies which could be of aid to the exploration geologist concerned with the evaluation of base metal potential in the range.

LIMITATIONS OF THE STUDY

In a presentation such as this, it is necessary to establish certain limitations to the overall study. The reasons for this are twofold. First, this work is concerned primarily with environmental controls for base metal deposition in the range. By definition, then, precious metal occurrences are purposely ignored. This immediately rules out discussions of such important mining districts as Swauk-Blewett, Mount Baker-Red Mountain, and Monte Cristo. At a future date an attempt will be made to undertake an integrated environmental study of both base and precious metal deposits in the range. Secondly, a discussion of all base metal occurrences in the range is not considered necessary. Specific property data are presented only when it is particularly important to outline examples of the various hypotheses presented. Therefore, in this paper the exclusion of certain properties or districts does not in any way reflect on the potential of these areas. Furthermore, the purpose is not to outline exploration targets. Matters of area evaluation must be left to the individual, whether professional or amateur.

Besides those deposits and environments discussed in this paper, various other types of metal deposits are found in the range. The limited scope of this study precluded detailed investigations of deposits such as: copper deposits associated with ultramafic rocks, lead and zinc mineralization in transverse structural belts such as the Skagit Queen-Thunder Creek-Horseshoe Basin areas, residual concentrations of iron and nickel on the weathered surfaces of ultramafic rocks, and mercury deposits related to Tertiary volcanic activity.

FIELD AND LABORATORY WORK

Field studies for this project began in July of 1958 and continued, on a seasonal basis, through December of 1966. During much of this period (1959-1964) the author was employed by Bear Creek Mining Company and directed many of its exploration projects in the Cascades. From 1966 to 1968 he was engaged in independent research on problems pertaining to economic geology in the range. During the latter period, many of the ideas presented in this paper were formulated.

An exhaustive literature search on Cascade geology was conducted. The principal reference materials consisted of University of Washington geology theses. Many of these data were transferred to a geologic overlay series on U.S. Forest Service planimetric maps (1:31,680). Other information that was considered reliable was also added to these base sheets.

Field mapping was done on aerial photographs, U.S. Forest Service planimetric maps (1:31,680), U.S. Geological Survey topographic sheets, and, when required, on specially prepared contour maps. At certain properties, where small-scale mapping was accomplished, base control was established in the field, mostly by Brunton-tape traverses but occasionally by theodolite. Most of the reconnaissance data were eventually transferred to a suitable base map series.

Over 2,000 rock specimens were collected in the field. Several hundred of these were analyzed for base metal content. During the 1965 and 1966 seasons, a considerable number of stream sediment and soil samples were collected from various parts of the range to establish some general background geochemical data.

The largest part of the laboratory research was devoted to wall rock alteration studies and the delineation of the major Cascade alteration systems. More than four hundred thin sections were prepared and examined. Plagioclase compositions were determined with the aid of a universal stage. Modal analyses were determined on the basis of a minimum 600-point count, using the Chayes (1956) method. Staining tests on potash feldspar and plagioclase facilitated modal counts. These data served as a basis for calculations of major oxide compositions of the principal alteration types. Some of the modes were programed into a computer to check the earlier chemical calculations. A close similarity between the calculated and computer data was found to exist.

A representative suite of hand specimens and associated thin sections illustrating the principal alteration types in the range has been placed on open file at the offices of the Washington Division of Mines and Geology, in Olympia.

ACKNOWLEDGMENTS

To properly acknowledge the help of various individuals who have supplied information on Cascade geology and ore deposits would necessitate a lengthy addendum. Therefore, a general note of recognition is extended to all those geologists who have worked in the Cascade Range, often under difficult and uncomfortable conditions.

The author wishes to express special gratitude to Dr. Peter Misch, of the University of Washington, who, more than anyone else, has contributed to the geologic understanding of the range. Dr. Misch also critically reviewed parts of the manuscript.

This study was made possible under a special grant by the State of Washington Department of Conservation, Division of Mines and Geology. In particular, Mr. Marshall T. Huntting was instrumental in initiating the grant and added constant encouragement. Discussions with other members of the division were mutually beneficial. The division also prepared the final drafts of the illustrations and furnished the base map for Figure 2.

The author acquired much of his information on Cascade ore deposits during his employment (1959-1964) as an exploration geologist for Bear Creek Mining Company.

Mr. W. K. Lee aided in the preparation of the illustrations and offered valuable criticism on the paper. Mr. W. T. Russell did the preliminary drafting on Figure 2. Dr. A. J. Sinclair, of the University of British Columbia, kindly consented to make a computer analysis of the alteration types. Dr. J. A. Vance reviewed the sections on Cascade geology. Dr. D. W. Cole provided information on Cascade soil development. Helicopter pilot R. E. Nokes provided amicable companionship and very helpful assistance during much of my mountain work in 1965 and 1967.

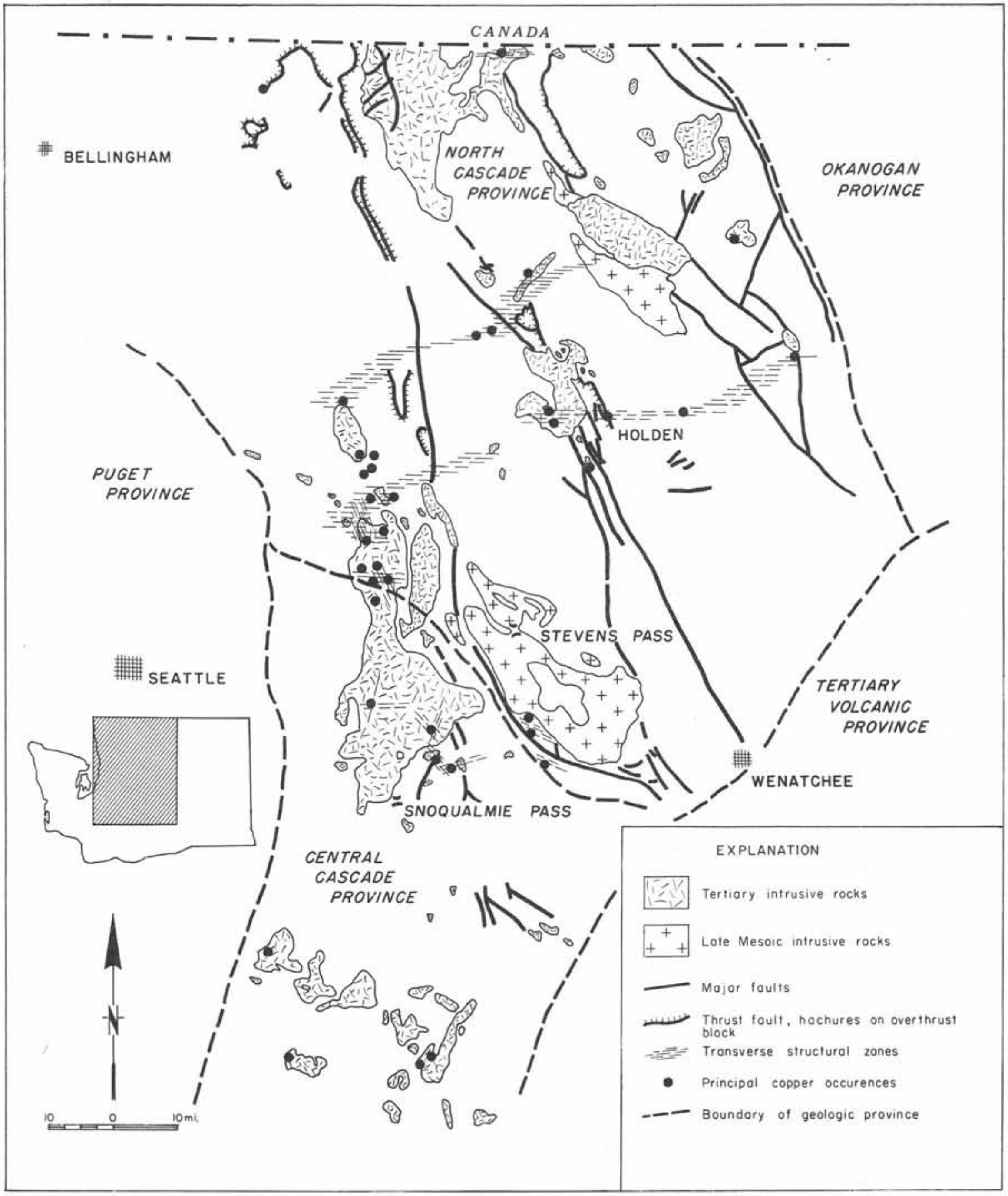

FIGURE 2.—Geologic environments for ore deposits, Cascade Range, Washington.

GEOLOGY

GEOLOGIC PROVINCES

The Cascade Range of Washington (see Fig. 2) may be divided into two principal geologic provinces:

(1) the North Cascades, composed predominantly of pre-Tertiary metamorphic rocks and Late Cretaceous-Tertiary intrusive rocks, and

(2) the Central Cascades, composed predominantly of unmetamorphosed Tertiary supracrustal and intrusive rocks.

Figure 3 shows the general distrubution of rock units in the range.

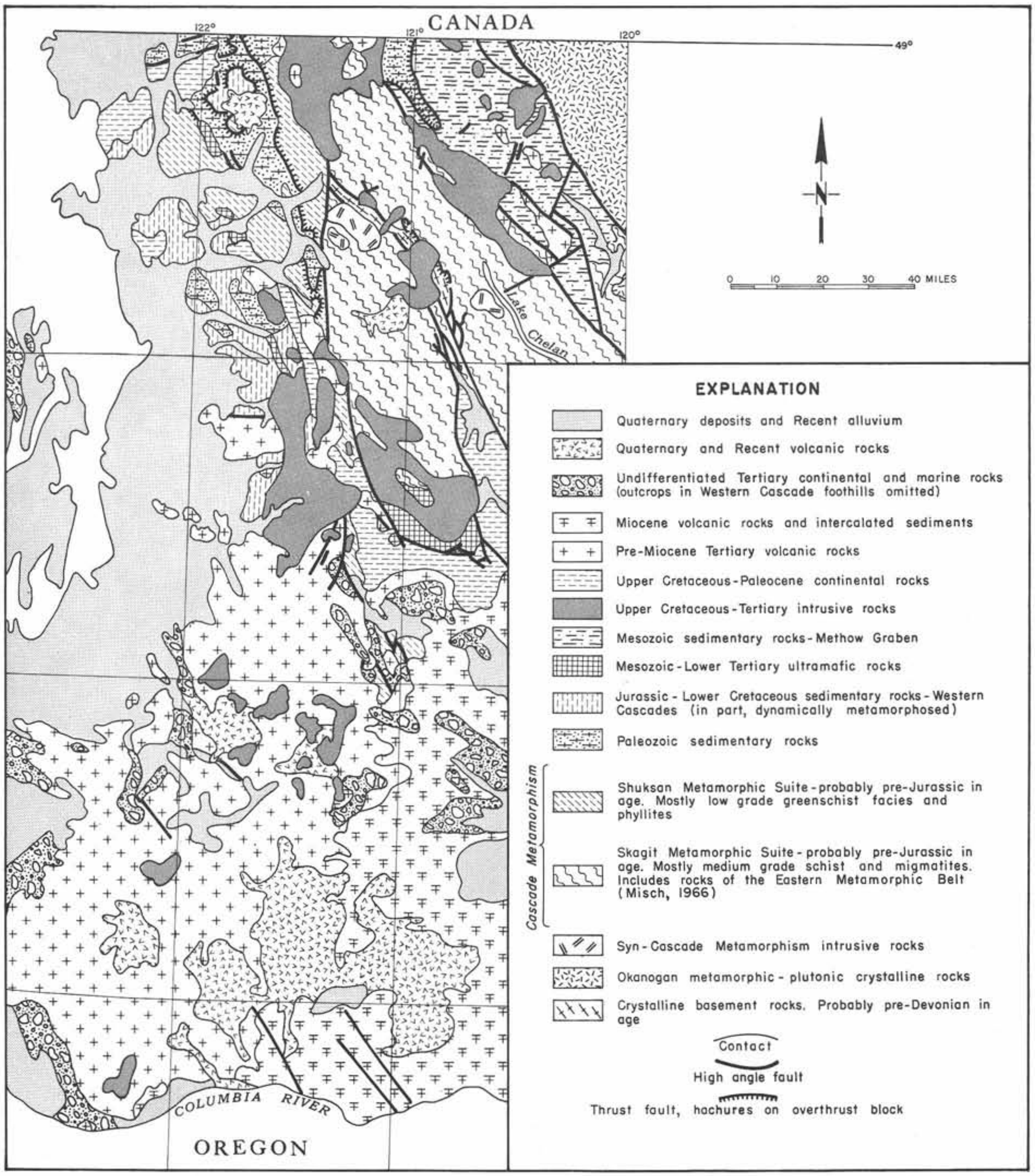

FIGURE 3.—Generalized geologic map of the Cascade Range of Washington. Modified from USGS and others, 1966.

The Cascades are bounded on the east by the Okanogan and Tertiary Volcanic Provinces. The Okanogan Province is characterized by a high-grade heterogeneous complex of schists and migmatitic gneisses and various low-grade meta-igneous and metasedimentary rocks. The Tertiary Volcanic Province consists almost exclusively of Mio-Pliocene basalts. Locally, along the margins of the basalt zone, intercalated lacustrine and fluviatile deposits occur. At the top of the basalt column along the western edge of the province, andesite volcanic debris has accumulated (Smith, 1903a).

The Cascade provinces are bounded on the west by the Puget Lowlands Province, consisting chiefly of Tertiary sedimentary and volcanic rocks, predominantly of marine origin.

Other than the foregoing, which is presented to acquaint the reader with the boundary provinces of the Cascade Range, no further mention of these peripheral areas is necessary.

GENERAL CONSIDERATIONS AND DEFINITION OF TERMS

Classification of the granitic rocks in this paper is based predominantly upon the ratio of potassium feldspar to total feldspar in the rock. The following classification will be used herein:

Ratio of K-feldspar to total feldspar (percent)	Rock name
> 60	Granite
40 - 60	Quartz monzonite
10 - 40	Granodiorite
< 10	Quartz diorite or diorite

The distinction between quartz diorite and diorite is based upon the quartz content. Quartz diorite contains more than 10 percent quartz, whereas diorite contains less than 10 percent quartz.

The following terms are defined so as to eliminate misinterpretation of their usage in this paper:

Allochemical - a metamorphic term referring to those rocks in which metamorphism has taken place with conspicuous chemical change to the original (i.e., parent) rock.

Allochthonous - in general, a term applied to rocks of which the dominant constituents have not been formed in situ. As a tectonic term, a structural block (i.e., allochthon) that has been moved a substantial distance (e.g., major overthrust).

Anatexis - the generation of a granitic magma as a final climax of granitization and mobilization.

Autochthonous - the opposite of allochthonous, referring to rocks formed essentially in situ. As a tectonic term, a structural block (i.e., autochthon) that has moved a comparatively short distance.

Chlorite - unless otherwise specifically stated, a broad group of phyllosilicates forming an extensive isomorphous series exhibiting a high degree of atomic substitution, particularly with magnesium and ferrous iron (Berry and Mason, 1959).

Deuteric alteration - metasomatic alteration occurring in igneous rocks, implied to be genetically related to late magmatic emanations of the same intrusive cycle. Generally highly silicic and potassic in nature.

Hydrothermal alteration - alteration, not necessarily related to a magmatic source (but in most cases, a genetic relation is apparent) that is superimposed on pre-existing rock. The term alteration (all inclusive) is used in this paper to denote mineralogical changes within solid state material in a sulfide deposition environment. Hornfelsing, mylonitization, or normal metamorphic processes are not included, although it is obvious that both deuteric and hydrothermal alteration are types of metamorphism, albeit specialized ones.

Isochemical - a metamorphic term referring to rocks whose metamorphism has taken place without significant or conspicuous change in chemical composition.

K-feldspar - a broadly used term referring to the alkali feldspar group. As used in this report, refers to potassium-rich orthoclase.

Ore - a term rather loosely used in this paper to indicate a significant quantity of valuable metal occurring in its natural environment. Because of variable economic factors, the term as used here does not necessarily imply material that can be extracted at a profit.

Orthoclase - potassium-rich monoclinic feldspar. Bowen and Tuttle (1950) noted that the high-temperature solid solution of orthoclase-albite tends to separate with decreasing temperature to produce separate potassium-rich and sodium-rich feldspar lamellae. The term orthoclase, as used here, refers to the lower temperature potassium-rich alkali feldspar that commonly forms as an alteration product in a high-potassium environment.

S plane - referring to metamorphic shear planes based upon Sander's (1930) classification system. Metamorphic rocks commonly acquire new structure owing to tectonic deformation. The planar structures thus developed are termed foliation planes, planes of schistosity, or "S" planes. It is convenient to use the "S" plane terminology in that a geologist can designate various planes of shear as S_1, S_2, etc., depending on their paragenetic relation to each other.

Sericite - unless otherwise stated, fine-grained muscovite forming at the expense of pre-existing silicate minerals.

Synkinematic metamorphism - metamorphism taking place during orogeny and accompanied by differential rock deformation. Metamorphism outlasting the synkinematic stage is termed post-kinematic.

Transverse - relating to structural systems crosscutting the regional structural grain.

OUTLINE OF GEOLOGY IN THE NORTH CASCADES

The crystalline rocks forming the axial zone of the North Cascade Range can be basically subdivided into three groups. These prinicpal subdivisions were originally studied and described by Misch (1952, 1956, 1959, 1960, 1963, 1966, and oral communication) in conjunction with his geologic studies of the northern part of the North Cascades. These groups are:

(1) pre-Middle Devonian rocks (Yellow Aster Complex), which were crystalline prior to regional metamorphism (Cascade cycle) of possibly latest Permian to Triassic (definitely pre-Middle Jurassic) age,

(2) crystalline rocks produced during the Cascade metamorphic cycle, and

(3) plutonic rocks produced during the Late Cretaceous and Tertiary periods of granitic evolution.

Most of the rock units within the area of the North Cascades are similar in character, but not necessarily in age, to the great complex of metamorphic and igneous rocks that can be traced along the axial zone of the West Cordilleran Geosyncline from northern California to Alaska.

The aforementioned rock units are exposed primarily in northwest-southeast-trending belts, thus defining regional trends produced during the Cascade cycle. Although the axial belt of migmatitic and plutonic rocks trends northwestward, the western margin of this zone includes a series of arcuate projections that diverge from the dominant structural trend of the range. These arcuate projections, which resemble a reverse "S" (Ƨ), may represent minor structural adjustment within the crystalline block during the development of the regional trends within the geosynclinal system. Additional structural complications along the western margin of the axial belt have been caused by middle Cretaceous thrusting and Tertiary faulting, which have brought rocks of different metamorphic grades and facies into juxtaposition.

On the eastern side of the North Cascades, the metamorphic rocks are in fault contact with the down-dropped Methow block, consisting of a thick Cretaceous sequence, mostly marine in origin (Barksdale, 1948, 1958, 1960; and Misch, 1966). Numerous Tertiary intrusive plutons have invaded the Cretaceous rocks in the Methow-Pasayten area.

The southeastern end of the North Cascade Province is referred to as the Mount Stuart uplift. This area has been geographically assigned to the Central Cascade Range, but its geologic history (Smith, 1904, and restudied in part by Pratt, 1958) is more akin to that of the North Cascades. Small inliers of North Cascade rocks still occur west and south of this region, the southernmost known one being the Easton Schist unit mapped by Stout (1964) southeast of Snoqualmie Pass.

Misch (1952, 1963, 1966, and oral communication) believes that the geologic history of the crystalline rocks in the North Cascades comprises the following stages:

The oldest rocks in the range are a pre-Middle Devonian heterogeneous metamorphic-plutonic complex (Yellow Aster Complex). These crystalline rocks occur as both autochthonous belts within the Cascade Metamorphic Suite and allochthonous tectonic slices along the western flank of the range. The basement metamorphics may have been subjected to an early granulite facies metamorphism, the record of which is scattered and disconnected. Later amphibolite facies metamorphism has affected almost all of the basement metamorphics. These basement rocks are metaigneous and range in composition from ultramafic to trondhjemitic orthogneiss, most being hornblendic. The older metamorphics were intruded by a series of predominantly quartz dioritic plutons. These intrusions postdate all basement metamorphism but predate deposition of the supracrustal parent materials of the Cascade Metamorphic Suite.

Misch (1966, p. 102-103) has divided the Cascade Metamorphic Suite into three main subdivisions. The westernmost subdivision is the Shuksan Metamorphic Suite (bounded on the west by the Shuksan thrust), composed of phyllites and of low-grade metabasalts in a subfacies of the blueschist facies. East of the Shuksan Suite and separated by a major dislocation zone (Straight Creek fault) are the rocks of the Skagit Metamorphic Suite, ranging from greenschist to amphibolite facies (predominantly medium-grade). The easternmost subdivision has been designated by Misch the eastern metamorphic belt and consists of low- and medium-grade rocks, the metamorphism of which postdates Skagit metamorphism. The eastern belt is separated from Skagit rocks by another major structure, the Ross Lake fault zone.

Rocks of the Skagit Metamorphic Suite form the backbone of the main range. Initial metamorphism of Skagit rocks during the Cascade cycle was isochemical and synkinematic, the grade of which increased from low-grade in a part of the western sector of the belt to medium- and locally high-grade in the central and eastern sectors. Most of the rocks subjected to this metamorphism were supracrustal, but also there were pre-metamorphic intrusive bodies ranging from ultramafic to trondhjemitic in composition. In addition, much of the belt was subjected to extensive synkinematic and post-kinematic granitization, leading to the production of genetically complex migmatitic and granitic masses. Climaxing this period of granitization was localized mobilization of authochthonous material and intrusion of allochthonous igneous material interpreted as having formed by anatexis at lower levels. Generally, these late metamorphic intrusives were subjected to minor deformation associated with the latest stage of the Cascade cycle.

The autochthonous belts of basement rock within the Skagit Suite, in addition to being subjected to regional metamorphism, have been overthrust to the northeast along much of their extent (Tabor, 1963; Grant, 1966; and Misch, 1966). Misch believes that these structures are synchronous with Skagit metamorphism.

The rock's age of the supracrustal parent rocks of the Shuksan and Skagit Suites is unknown. This supracrustal material was composed of predominantly clastic sedimentary rocks and basic volcanics. Volcanic rocks were subordinate in the parent material of the Skagit Suite. In overall lithologic aspect, many of the metasedimentary and metavolcanic sequences in the Shuksan and Skagit Suites compare with strata in the upper Paleozoic Chilliwack Group, but sufficient dissimilarities exist to prohibit correlation.

The age of metamorphism of the Shuksan and Skagit rocks is not known, but according to Misch the most probable age is late Permian to Early Triassic. A probable upper age limit for the Shuksan metamorphism is pre-Middle Jurassic. It is not known whether the Shuksan metamorphism and the Skagit metamorphism are synchronous, as the Shuksan rocks are separated from Skagit rocks by the post-metamorphic Straight Creek fault. Metamorphism in the narrow eastern belt is definitely post-Skagit and was associated with middle to early Late Cretaceous orogeny, involving regional thrusting (Shuksan and Church Mountain thrusts) on the west flank of the range and major faulting (Ross Lake fault) and minor thrusting (Jack Mountain thrust) on the eastern flank.

Rocks of the Shuksan and Skagit Suites can be traced south from their type areas for more than 80 miles. The Shuksan rocks occur as discontinuous inliers along the southerly continuation of the Shuksan belt. The Skagit rocks extend southward as a heterogeneous series of schists and migmatites to the central part of the Mount Stuart uplift.

Several periods of ultramafic intrusive activity have occurred in the range. The earliest of these are pre-Skagit metamorphism (for example,see Grant, 1966). In the center of the Mount Stuart uplift, a large peridotite mass of batholithic dimensions was emplaced prior to the intrusion of the Late Cretaceous Mount Stuart Batholith (Smith, 1904). In the northwestern Cascades southwest of Mount Baker the Twin Sisters Dunite intruded the Late Cretaceous-Paleocene continental sedimentary rocks of the Swauk Formation (Ragan, 1961). Vance (1957) described early Tertiary ultramafic dike activity south of Darrington, in the Jumbo Mountain area.

Postdating the Shuksan and Skagit metamorphism in the North Cascades is a complex history of deposition and orogeny. In Late Triassic to Early Jurassic time, a thick section of marine eugeosynclinal rocks was deposited along the western flank of the pre-existing metamorphic core of the range. Following the marine deposition, a thick sequence of andesitic-dacitic volcanic flows and breccias and subordinate intercalated marine slates and graywackes was deposited. Misch (1966) named this unit the Wells Creek Volcanics. Unconformably overlying the volcanic rocks are approximately 5,000 feet of Late Jurassic-Early Cretaceous sedimentary rocks that Misch (1952) named the Nooksack Group. Misch believes the Nooksack rocks were deposited during a period of rapid marine accumulation. Above the Nooksack basal conglomerate is a heterogeneous series of predominantly volcanically derived graywackes and siltsones, with local thick conglomerates.

Postdating Nooksack deposition was the intra-Cretaceous orogenic cycle. On the western flank of the range, large-scale west-yielding thrusting occurred. The two major thrusts are the Shuksan thrust, which brought phyllite and greenschist of the Shuksan Metamorphic Suite and imbricated basement crystalline rocks over Paleozoic rocks, and the Church Mountain thrust, which brought Paleozoic rocks over Mesozoic rocks. The southern continuation of the Shuksan thrust belt has been traced conclusively as far south as the Skykomish area, where several klippen of crystalline basement rocks over Paleozoic rocks were mapped by Yeats (1958, 1964). Horizontal displacement of the Shuksan thrust from its root zone exceeds 30 miles.

On the east side of the metamorphic-plutonic core of the range, major faults associated with Cretaceous orogeny are not as well exposed. The northwest-trending Ross Lake fault zone can be traced intermittently over a strike length of more than 85 miles in the Washington Cascades. A northward extension of this zone into Canada may well exceed 100 miles. In the Ross Lake area, the eastward-directed Jack Mountain thrust (Misch, 1952, 1966) has issued from the Ross Lake fault zone, bringing upper Paleozoic rocks over Lower Cretaceous rocks. Horizontal displacement of the Jack Mountain thrust is on the order of 6 miles.

Misch (1966) summed up the implications of this Cretaceous orogeny in its regional setting. The earlier crystalline core of the range is bounded on both its eastern and western flanks by major crustal breaks. If these ruptures extend to the base of the crust, the Cascade's crystalline core represents a compressively uplifted crustal wedge.

Post-metamorphic Late Cretaceous to Miocene intrusive masses are distributed throughout the extent of the North Cascades. The intrusive rocks are typically calc-alkaline and mainly quartz dioritic-granodioritic (Misch, 1965). Because of the significant relation of these intrusive plutons to ore deposition in the range, a more detailed discussion of their petrology and physical characteristics is given in a later part of this paper.

Following the Cretaceous orogeny, continental sediments of late Upper Cretaceous-Paleocene age were deposited in thicknesses of as much as 20,000 feet in a continuous northwest-southeast belt across the range. These rocks, originally described by Russell (1893), are generally referred to as the Swauk Formation in the Central Cascades and the Chuckanut Formation in the Bellingham-Mount Baker area. The name Swauk has priority and should be used exclusively for all correlative rocks of this type in the range.

TABLE 1. — Generalized columnar sections of certain Tertiary stratigraphic units of the Central Cascades

		Hammond, 1963				Fiske and others, 1963		Foster, 1960		
		West Section - Central Cascades		East Section - Central Cascades		Mount Rainier National Park		Western Area		Eastern Area
Pleistocene						Stratovolcanic rocks—mainly pyroxene andesite, locally olivine andesites				
Pliocene		? — Erosion surface — ? Ellensburg Formation: Lava flows, volcanic sediments				Unconformity Mio-Pliocene volcanic rocks locally, welded tuffs				Erosion surface Yakima Basalt: Basalt flows and minor interbedded sedimentary rocks
Early Miocene		Unconformity *Cougar Mountain formation Lava and breccia flows, subordinate conglomerates, and sandstones				Unconformity Fifes Peak Formation: Basalts, andesite flows, local rhyolite flows, tuffs, volcanic breccias, sandstones, and siltstones		Erosion surface		
Oligocene	Keechelus Volcanic Group	Unconformity *Snow Creek formation: Tuff breccias, volcanic sediments, lava, and breccia flows		Erosion surface *Snow Creek formation		? — ? — ? Stevens Ridge Formation: Rhyoclastic flows, subordinate volcanic breccias, sandstones, and siltstones		Keechelus Andesite: Basalt and andesite flows, tuffs and breccias		Unconformity
Eocene (Late)	Keechelus Volcanic Group	*Stampede tuff: Composite ignimbrite		*Stampede tuff				Unconformity		Roslyn Arkose: Arkosic sandstone
Eocene (Late)	Keechelus Volcanic Group	Unconformity *Eagle Gorge andesite: Lava and breccia flows		Unconformity				Naches Formation: Interbedded basalt, sandstone, conglomerate, and rhyolite		Teanaway Basalt: Basalt flows and interbedded basaltic pyroclastics
Eocene (Late)	Keechelus Volcanic Group	Unconformity *Huckleberry Mountain formation: Tuff breccia, volcanic sediments, subordinate lava, breccia flows, and tuffs	Snoqualmie batholith (predominantly quartz diorite)	*Huckleberry Mountain formation	Snoqualmie batholith		Tatoosh pluton	Mt. Catherine Rhyolite: Rhyolite flows, tuff, and breccia	Snoqualmie Granodiorite	Unconformity
Eocene (Late)	Keechelus Volcanic Group	*Enumclaw formation: Lava and breccia flows, subordinate tuff, breccia, volcanic sediments, and tuffs		Naches Formation: Epiclastic volcanic rock, breccia flows, subordinate arkose, and tuff						Silver Pass Volcanics: Andesite and more felsic flows, tuff, and breccia
Eocene		*Mt. Catherine tuff: Composite ignimbrite		*Mt. Catherine tuff				Unconformity		
Eocene (Middle)	Puget Group	Unconformity Tukwila Formation: Epiclastic volcanics		Unconformity		Unconformity				Unconformity
Eocene (Middle)	Puget Group	Tiger Mountain Formation: Sandstones, siltstones, coal, minor epiclastic volcanics		Guye Formation: Sandstone, siltstone, pumice, chert, shale		Ohanapecosh Formation: Volcanic breccia, sandstone, siltstone, local lava flows		Guye Formation: Sandstone, shale, and conglomerate		
Paleocene		Unconformity Swauk Formation: Continental sediments		Unconformity Swauk Formation		? — ? — ?				Swauk Formation

* Informal name

An early Eocene, post-Swauk orogeny was responsible for widespread folding and faulting along the northwestern flank of the range (Miller and Misch, 1962). This orogeny may also have caused large broad folding in the crystalline rocks in the core of the range (Misch, 1966).

Postdating the early Eocene deformation, several depositional and weak orogenic cycles are recognized. In general, post-Paleocene Tertiary deposits are rare in the North Cascades; this is in marked contrast to the Central Cascades, where extensive Eocene-Oligocene volcanic rocks have accumulated. The only volcanic rocks in the northern region correlative to the thick volcanic sequences to the south are the middle Tertiary (probably Oligocene) Hannegan Volcanics (Misch, 1952, 1966), the (?) Oligocene Skagit Volcanics (Daly, 1912) and farther south, the middle Eocene Barlow Pass Volcanics of Vance (1957).

Late Cenozoic uparching produced the present Cascade Range. The axis of the uplift was north-south, plunging south. The south-plunging axis caused maximum uplift in the North Cascades, thus exposing the older rocks. Synchronous with this uparching may have been block faulting or rejuvenation of movement along older structures.

Pleistocene stratovolcanoes such as Mount Baker (Coombs, 1939) and Glacier Peak (Ford, 1959) were superimposed on topography that already contained the gross features of the present relief. Glaciation and water erosion have been significant in carving the present land forms.

OUTLINE OF GEOLOGY IN THE CENTRAL CASCADES

Reconnaissance geological coverage in the Central Cascades of Washington is not as complete as that in the North Cascades. Nevertheless, sufficient mapping has been accomplished to present a reasonably complete picture.

In general, the Central Cascades are composed of latest Cretaceous and Tertiary supracrustal rocks that have been invaded by Eocene to Miocene intrusive plutons. Pre-Tertiary rocks are rare, most occurring as small fault-bounded uplifted blocks, within which pre-Tertiary imbricate structure can be recognized (e.g., Stout, 1964). An exception to this is the southern extension Mesozoic eugeosynclinal depositional sequence (Misch's Nooksack Group) cropping out along the western flank of the Cascades between the Snoqualmie and Stevens Pass highways. In the Snoqualmie Pass area, small occurrences of possibly upper Paleozoic sedimentary rocks (?Chilliwack Group) were mapped by Danner (1957).

With the exception of the aforemention rocks, the oldest rocks in the Central Cascades are those of the Late Cretaceous-Paleocene Swauk Formation. These continental sedimentary rocks, consisting primarily of sandstones, siltstones, argillites, and conglomerates crop out in the northern part of the province. Unconformably overlying these rocks are the heterogeneous volcanic formations and associated sedimentary strata, varying in age from Eocene to Pleistocene.

Table 1 shows the approximate relation of some of the varied stratigraphic units in the Central Cascade Province. With the exception of the Upper Cretaceous-lower Tertiary rocks consisting predominantly of clastic sediments derived from continental rocks, the middle to upper Tertiary column comprises a complex variety of volcanic flows and breccias and sedimentary rocks.

Hammond (1963) has summed up the Tertiary history in the northern Central Cascade area as follows. Although minor divergences may be found in other areas of the Central Cascade Province, the overall historical patterns are probably similar.

> During late Eocene time, arkosic and volcanic sediments were deposited on a gently subsiding flood plain. Marine rocks are absent.
>
> A weak Eocene orogeny resulted in deformation of these supracrustal rocks, mainly by moderate folding and local faulting.
>
> Following this orogeny the deposition of extensive sheets of rhyodacite and dacitic ash took place, followed by volcanic eruptions, from which great quantities of extrusive rocks were accumulated. Local interstratification of arkosic sedimentary rocks indicates that subsidence of the area was in progress at this time. The lave flows were overlain by a thick section of fragmental volcanic ejecta.

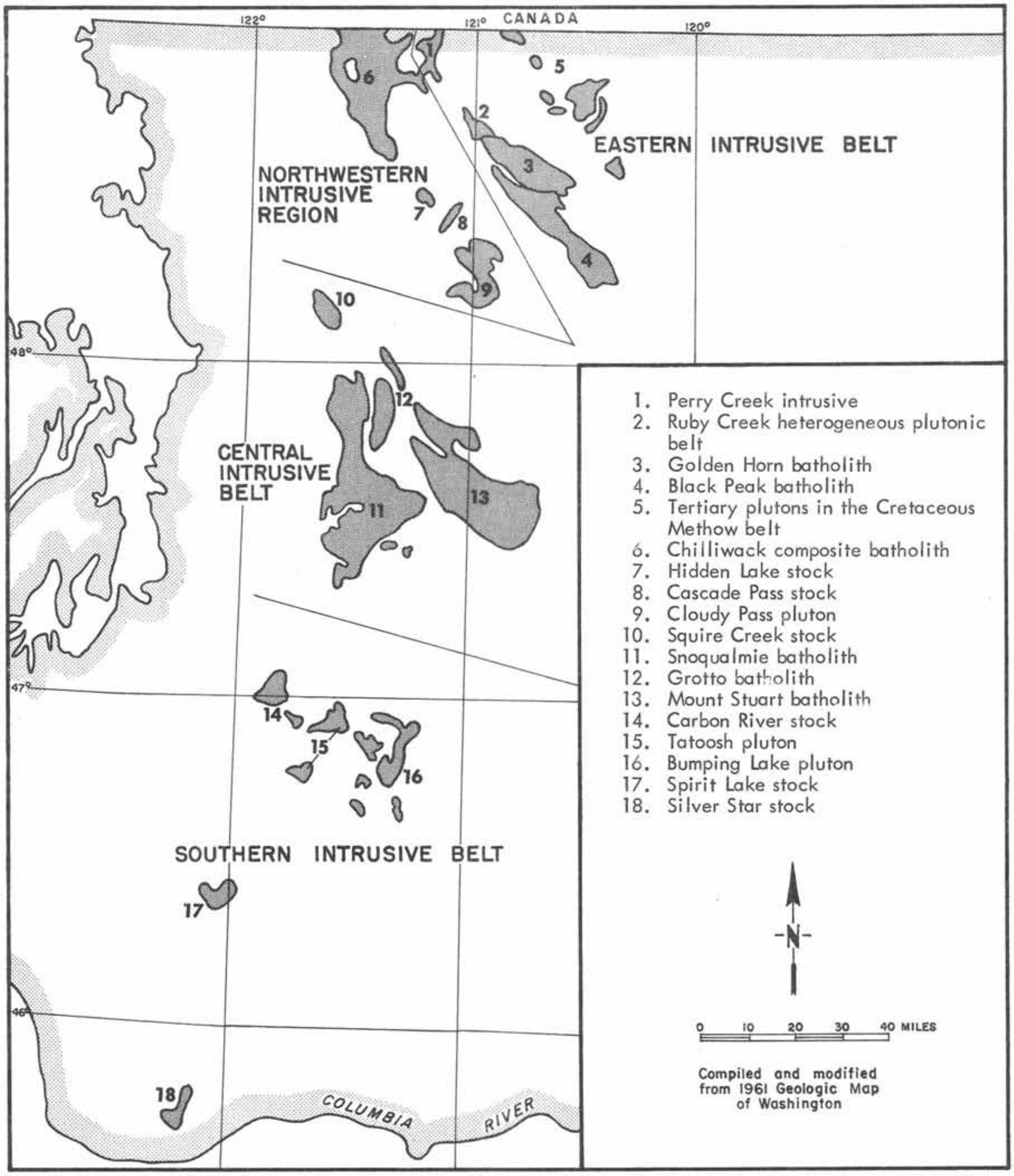

FIGURE 4. — Major intrusive belts and major plutons, Cascade Range of Washington.

Near the close of Eocene time, the area was buried under a thick succession of andesitic lavas. Mild warping of the area occurred during this same period and continued after the cessation of extrusive activity.

Late Eocene-early Oligocene dacitic ash deposition was followed by explosive volcanic eruptions. Accumulation of volcanic rocks may have continued, but the depositional record is interrupted by a hiatus extending into early Miocene time. Fiske and others (1963, p. 63), however, state that in the Mount Rainier area the Fifes Peak Formation was deposited during middle Oligocene through early Miocene.

Early Miocene volcanic flows were followed by moderate deformation and the emplacement of the Snoqualmie batholith. Synchronous with batholithic activity was deformation responsible for many of the major fold and fault patterns in the area. Uplift resulted in extensive erosion, causing many of the gross drainage patterns still present.

Late Miocene-early Pliocene weak deformation followed the same northwesterly trends established in late Eocene and reinforced during middle Miocene time.

Pliocene accumulation of volcanic sediments and local flows predated the late Pliocene uparching of the Cascade Range on a north-south axis, plunging south.

Pleistocene volcanism (Coombs, 1935), glaciation, and erosion resulted in the current landforms.

LATE CRETACEOUS-TERTIARY INTRUSIVE ACTIVITY

Any student of ore deposits in the Cascade Range certainly must consider the Late Cretaceous-Tertiary period of granitic evolution as the most important geological event in the area's complex history. The intrusive rocks are typically calc-alkaline and mainly quartz dioritic to granodioritic.

As most of the more significant ore deposits in the range are, at least in part, associated with these plutons, it is necessary to have a fundamental understanding of the igneous petrology of these masses. On the whole, the intrusions are remarkably similar in character and petrogenetic history. The distribution of the principal intrusive masses in the Washington Cascades is shown in Figure 4.

North Cascades

In the North Cascades, Misch (1966) has separated the younger intrusive masses into two main belts. The eastern belt includes those plutons that rose along the Ross Lake fault zone. The oldest rocks appear to be those of the quartz dioritic to granodioritic Black Peak batholith and have a tentative age of Late Cretaceous based upon a radiometric measurement of biotite. North of the Black Peak batholith, Misch has mapped a complex series of small intrusions ranging in composition from gabbro and diorite to quartz diorite and granodiorite. He has named them the Ruby Creek heterogeneous plutonic belt and suggested that these masses may at least in part be roughly synchronous with the Black Peak batholith. In contrast with the typically calc-alkaline intrusive rocks of this complex Cretaceous-Tertiary intrusive episode, the Golden Horn batholith consists predominantly of leucocratic highly alkaline granites. Golden Horn rocks intrude Black Peak rocks and Cretaceous strata. Age measurements on biotite by Curtis and others (1961) indicate an age near the Eocene-Oligocene boundary. Near the north end of the eastern intrusive belt, the quartz dioritic to granodioritic Perry Creek intrusive has been radiometrically dated at 30 m.y. by Kulp (Misch, 1966). The Perry Creek body is contiguous with the "Perry Creek phase of the Chilliwack batholith."

East of this eastern intrusive belt, Lower Cretaceous strata in the Methow-Pasayten area have been intruded by small stocks of igneous material of variable composition.

Misch's second intrusive belt, the western intrusive region, occurs mainly in the western part of the metamorphic core of the range. In order to clearly separate the various intrusive regions in the Washington Cascades, Misch's western zone of intrusions will be referred to as the northwestern region. The Chilliwack composite batholith is the largest of the intrusive masses in the northwestern region. Radiometric ages of the Chilliwack range from Eocene for the main, predominantly quartz dioritic phase to 30 m.y. for the younger Perry Creek phase. North of the 49th parallel, Baadsgaard and others (1961) have reported K-Ar dates of 18 m.y. for the northwesternmost part of the Chilliwack batholith. The relation of this part of the batholith to the main phase rocks is uncertain. South of the Chilliwack batholith, Misch (1966) mapped several small quartz diorite plutons; the Hidden Lake stock and the dikelike transverse pluton of the Cascade Pass Quartz Diorite (see also Tabor, 1963) are the largest of these. Kulp, according to Misch (1966), reported a 20 m.y. date from biotites of the Cascade Pass stock.

The southernmost pluton in this northwestern region is the Cloudy Pass pluton. The results of radiometric measurements on Cloudy Pass biotites by the U.S. Geological Survey (Crowder and others, 1966) ran 20 (±2) m. y. and 22 (±2.2) m. y. Much of the Cloudy Pass pluton has been studied in detail by the author (Grant, 1966), and the petrology of this mass is discussed later in this section.

Central and South Cascades

For the sake of continuity, it is proposed that two additional intrusive regions be added to Misch's northern belts. The central intrusive belt roughly coincides with the northern half of the Central Cascade Range, and the southern intrusive belt incorporates those small plutons in the southernmost part of the range in Washington.

In the central belt the earliest of the large intrusions is the pre-Swauk quartz dioritic calc-alkaline Mount Stuart batholith (Smith, 1903a, 1904), which is considered by most Cascade workers to be Late Cretaceous in age. Misch (1966) has suggested that the Mount Stuart rocks could be roughly contemporaneous with the Black Peak batholith.

The middle Tertiary Snoqualmie batholith of predominantly quartz dioritic composition is the largest intrusive complex in the Cascade Range, cropping out in a wide, northward-trending belt between Snoqualmie Pass and the Sultan Basin area. That area of the batholith north of the Stevens Pass highway was originally named the Index Granodiorite (Weaver, 1912), but it is considered by the author to be a northern extension of the Snoqualmie. Northwest of the Sultan Basin, a large stock of quartz diorite, informally called the Squire Creek stock by Vance (1957), is considered to be a satellite of the Snoqualmie batholith. Radiometric dates of the Snoqualmie plutonic complex vary considerably. Yeats (oral communication, 1962) reported a date of 38 m.y. (Rb-Sr) from quartz diorite exposed in the quarry near Index on the Stevens Pass highway. Misch (oral communication, 1967) obtained a K-Ar date of 34.3 (±1) m.y. on biotite from the Squire Creek stock. Biotites from the main-phase quartz diorite of the Snoqualmie have been dated by Baadsgaard and others (1961) at 18 m.y. by K-Ar methods. A 17 m.y. K-Ar age on biotite from the same part of the Snoqualmie batholith was reported by Curtis and others (1961).

East of the northern part of the Snoqualmie batholith, Yeats (1958) mapped a batholithic mass of hypersthene-augite tonalite, which he named the Grotto batholith. Although this mass appears to be separate from the Snoqualmie, it could represent an earlier intrusive phase of the Snoqualmie intrusive cycle.

Numerous other small intrusive masses have been reported in the central intrusive belt, but most, if not all, are considered to be satellitic stocks or plugs of the main batholiths.

The southern intrusive belt comprises those various smaller Tertiary plutons that have invaded Tertiary rocks. Of particular significance is the cluster of intrusions in and around Mount Rainier National Park. The best known of these is the Tatoosh pluton, studied by Fiske and others (1963). Biotites measured from quartz diorites in the pluton gave ages of 14.7 (±1) m. y. and 13 (±1) m.y. Two other similar, yet little known, intrusions in this area are the Carbon River stock and the Bumping Lake pluton. Farther south, near Mount St. Helens, the Spirit Lake stock and probably related small intrusions have not been studied in detail. At the southern end of this belt, the quartz dioritic-granodioritic Silver Star stock was studied by Felts (1939). No radiometric dating of these small stocks, except the Tatoosh, pluton, has been reported.

Age Correlation of Intrusions

Although the chronology of Cascade plutons is far from complete, there appears to be a general correlation of various intrusive episodes. The Late Cretaceous intrusive period included the emplacement of the Mount Stuart and probably the Black Peak batholiths with synchronous activity in the Ruby Creek heterogeneous plutonic belt. There is no evidence to indicate that any major intrusive events occurred during Paleocene time. The major period of Tertiary granitic evolution began in the Eocene and continued roughly to the Miocene-Pliocene boundary. The bulk of this activity took place west of the Late Cretaceous intrusive belt. Table 2 shows the principal intrusive chronology in the range based on available data.

TABLE 2. — Intrusive chronology of major Washington Cascade Late Cretaceous-Tertiary intrusions

	Rock Unit	Age	Reference
Canadian Border	Chilliwack batholith, latest phase	18 m.y.	Baadsgaard and others, 1961
↓	Chilliwack batholith, (main-phase quartz diorites)	Eocene	Misch, 1966
	Chilliwack batholith, late Perry Creek phase	30 m.y.	Misch, 1966
	Golden Horn batholith	Eocene-Oligocene boundary	Misch, 1966
	Cascade Pass Quartz Diorite	20 m.y.	Misch, 1966
	Cloudy Pass pluton	20 - 22 m.y.	Crowder and others, 1966
	Squire Creek stock	34.3 (±1) m.y.	Vance, oral communication, 1967
	Snoqualmie batholith	38 m.y. - north part	Yeats, oral communication, 1962
		18 m.y. - south part	Baadsgaard and others, 1961
		17 m.y. - south part	Curtis and others, 1961
	Mount Stuart batholith	Late Cretaceous	Smith, 1903a, 1904
South	Tatoosh pluton	13 - 14.7 m.y.	Fiske and others, 1963

Contacts

In general, the contacts of these masses are relatively sharp. Locally, however, particularly in the North Cascades, there have been noted gradational relationships between the intrusive and country rocks, resulting in the formation of contact migmatites or thermally reconstituted metaigneous rocks. Elsewhere, evidence of forceful intrusion is relatively common. The northern part of the Cloudy Pass pluton is characterized by classical intrusive breccias. Misch (1966) reported a large-scale intrusive breccia along the southern contact of the Golden Horn batholith, which also appears to have shouldered aside folded Cretaceous strata on its northeast side. Although not common, dike swarms of Golden Horn rocks locally invade the country rocks. Misch (1966) described large volumes of Golden Horn dike material intruding the rigid crystalline wall rocks on the southwest side of the Golden Horn batholith and suggested that this phenomenon could indicate tensional break-up due to uplift of the country rocks.

All the intrusions have, to some extent, altered the country rocks in the contact aureole. Contact metamorphism ranges from incipient low-grade hornfels facies to pyroxene hornfels facies. Perhaps the most widespread of the thermal metamorphism environments is hornblende hornfels facies. Low-temperature hydrothermal alteration, characterized by minor saussuritization of feldspar, is common in the outer part of the contact aureole. Where the intrusions are in contact with limey country rocks, skarn deposits may occur.

Speculations on Mode of Emplacement and Origin

With rare exceptions, the intrusive plutons of Late Cretaceous through Tertiary age appear to be wholly magmatic. Erikson (oral communication, 1966-1967), in his work on the Snoqualmie batholith, is doing an initial Sr ratio study in hope of determining whether the magma was derived from simatic or sialic crustal material. Results are not yet available.

Misch (1966) ruled out mobilization of Skagit Gneiss and resultant production of a neomagma as a possible origin of the Chilliwack composite batholith. Work in the northern part of the Cloudy Pass pluton suggests anatexis as a possible origin of some of that magma (Grant, 1966).

As to emplacement, several possible methods are suggested. The major problem centers around how the batholith found room. As previously mentioned, evidence of forceful intrusion has been noted in a few areas, but in most instances, however, the country rock was not deformed by intrusion. Evidence of major stoping has rarely been observed. Misch (1966, p. 141) suggests that wholesale uplifting of the roof could be a partial answer. It is difficult to visualize a rising magma front assimilating any and all country rocks. Magmatic homogeneity, which many of these plutons exhibit, would be next to impossible under these conditions.

Emplacement Levels

Most of the Late Cretaceous to Tertiary Cascade plutons appear to have been emplaced to relatively high levels in the crust. In the North Cascades the intrusive levels appear to be somewhat deeper, but probably not below 2 miles from the surface. Differential intrusive levels are in evidence along the contacts of the Chilliwack batholith, where Misch, (1966) reported a transitional zone of contact migmatitization with the Skagit Gneiss to the east, and a sharp intrusive contact

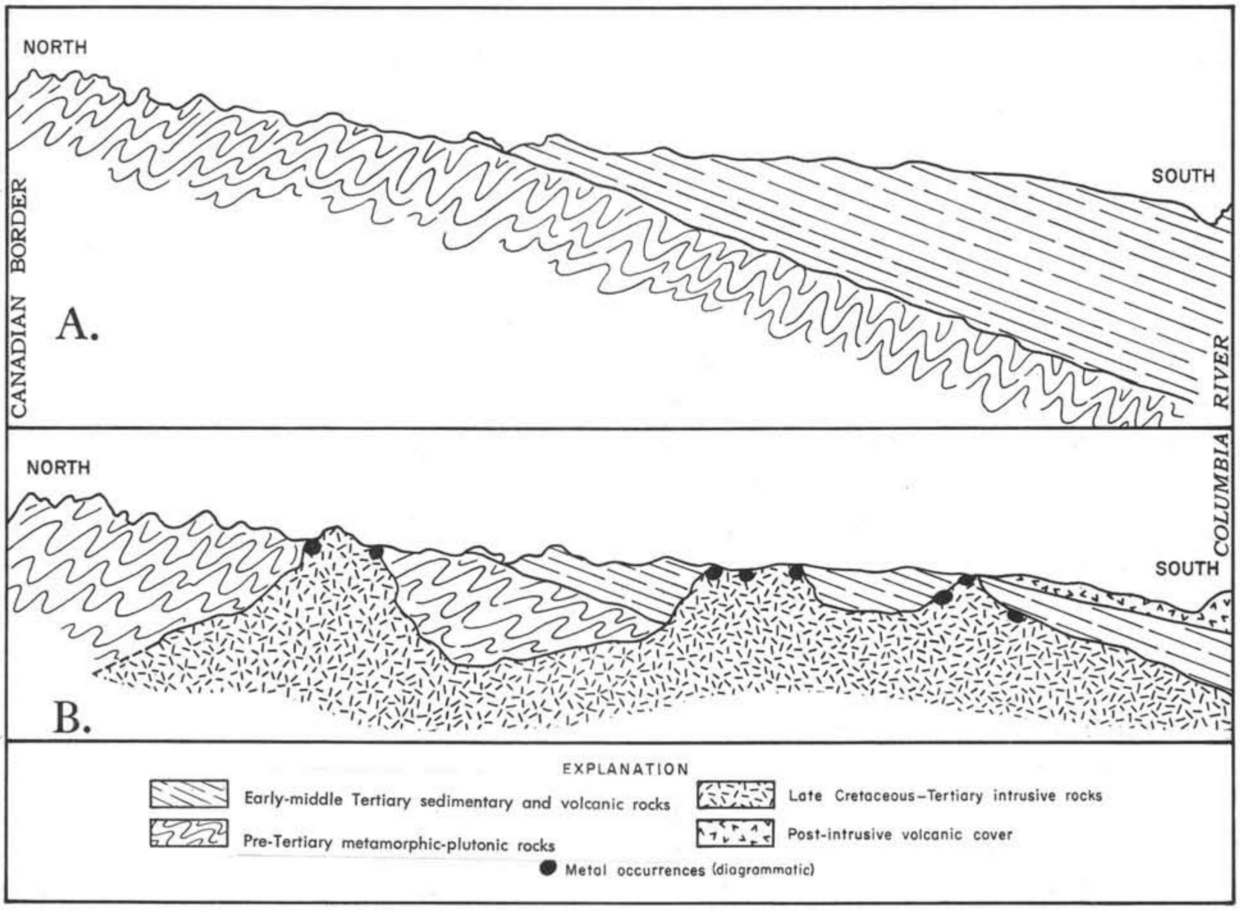

FIGURE 5.—Diagrammatic cross sections, looking east, through the Cascade Range of Washington.
(A) shows relation of Tertiary and underlying pre-Tertiary rocks with intrusive rocks omitted.
(B) shows relation of all three rock groups plus post-intrusive volcanics and metal occurrences.

with the Late Cretaceous-Paleocene Swauk Formation to the west. Tabor (1963) described an explosion breccia, probably occurring at a relatively high level, above the Cascade Pass stock. Cater (1960) described similar phenomena associated with the Cloudy Pass batholith.

Farther south in the range, the intrusive levels appear to rise to a level of perhaps less than 1 mile from the surface, and indeed, at least in two areas, the plutons have broken through to the surface. Fuller (1925) described a breaking through to the surface by the Snoqualmie batholith near its southwestern corner. Fiske and others (1963) reported that a part of the Tatoosh pluton broke through to the surface, resulting in the formation of explosion breccias. It would not be surprising if other breakthrough areas are discovered as the study of the southern plutons becomes more thorough.

The regional distribution of intrusive plutons in the Cascade Range, coupled with the extensive hornfelsing of much of the country rock, suggests that large areas may be underlain by post-metamorphic intrusive material. For example, Tabor (1961) noted that most of the rock units east of the crest between Agnes Creek (northern edge of the Cloudy Pass pluton) and Cascade Pass, a distance of more than 10 miles, has been subjected to either low-grade hornfelsing or hydrothermal alteration, even though no intrusive rocks crop out in that area. He attributed this alteration to nonexposed subjacent intrusive material and suggested a possible physical connection between the Cloudy Pass and the Cascade Pass plutons at depth. Farther south, between the Snoqualmie batholith and the plutons in the Mount Rainier area, widespread thermal alteration in the Tertiary volcanic section has been noted by various workers, suggesting the existence of subjacent intrusive rocks. Cater and others (1966) suggested that recurrent and probably broadly related intrusive activity was adding material to the core of the Washington Cascades, from Late Mesozoic to late Tertiary. Quaternary volcanism suggests that the intrusive activity is still continuing.

Figure 5 diagrammatically illustrates the possible regional distribution of Late Cretaceous-Tertiary intrusive material in the Cascades.

Petrology

Many of the Cascade intrusions may be considered composite in their magmatic history, in particular, those of middle-late Tertiary age. Misch (1966) reported multiple intrusive phases in the Chilliwack batholith comprising an early diorite and subordinate gabbro phase, a main-phase of predominantly quartz diorite, followed by a local leucogranitic phase and a late phase of quartz dioritic and granodioritic rocks resembling those of the main phase. In the Cloudy Pass pluton an early pyroxene-diorite phase later intruded by main-phase quartz diorite has been mapped (Grant, 1966). As a result of this second intrusion, the pyroxene diorite was locally recrystallized in hornblende hornfels facies. Late-stage residual magmatic volatiles, rich in potassium and silica, invaded the main-phase quartz diorite, deuterically altering it to granite and quartz monzonite. Locally, these rocks were mobilized, intruding the quartz diorite along favorable structural zones.

The three intrusive phases in the Cloudy Pass pluton are attributed to fractionation of a common parental magma. Volatiles and alkalies are thought to have been progressively concentrated in successively younger intrusions.

Erikson (1965) found at least three separate intrusive phases in the northeast corner of the Snoqualmie batholith. Chronologically, they consist of:

(1) an older pyroxene quartz diorite that was subjected to pyroxene hornfels facies alteration by the intrusion of:

(2) a main-phase quartz diorite-granodiorite mass that, in turn, was intruded by:

(3) a quartz monzonite stock that caused medium- to low-grade hornfelsing in the main-phase intrusion.

Vance (1961a) speculated on the origin of zoned granitic intrusions, which involved:

(1) crystallization from the margins inward, sealing in the released volatile phase, which, in turn, was forced downward with further crystallization, and

(2) the downward migration of alkalies and silica with the residual volatile components, and their subsequent enrichment of the magma at depth.

This hypothesis might account for some of the composite intrusive relations observed in the Cascade intrusions, but it must be emphasized that in many instances much of the volatile phase could have escaped to the upper levels of the pluton via structural avenues that facilitated solutional transfer.

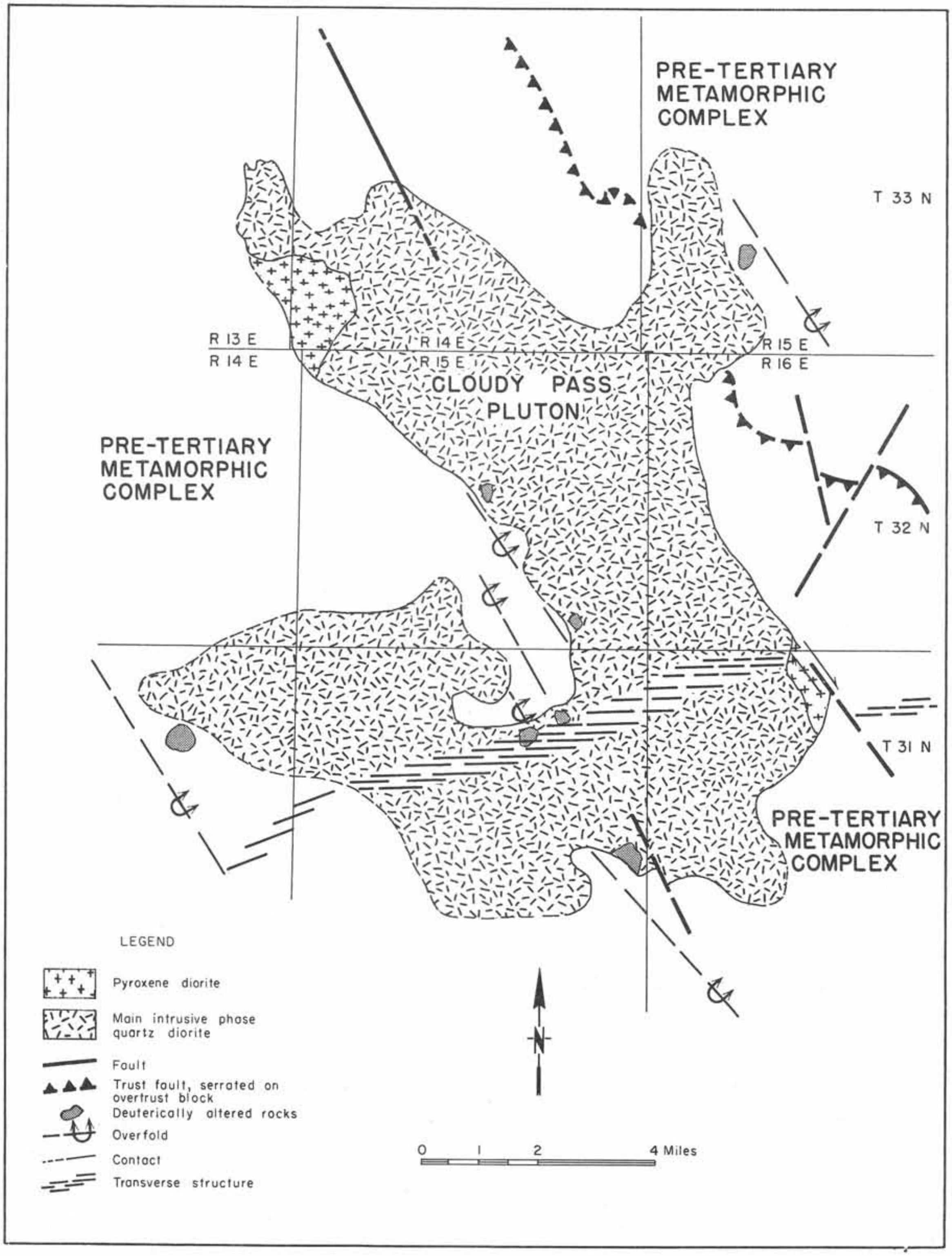

FIGURE 6.—Cloudy Pass pluton, North Cascades, Washington, showing distribution of three intrusive phases.

Cloudy Pass Pluton

In the following paragraphs, rocks of the Cloudy Pass pluton are briefly discussed. (For a more complete discussion, see Grant, 1966.) The intrusive relations found in the Cloudy Pass rocks are similar to those found in other Cascade intrusions and should serve to illustrate the general complexities. The reader must be cautioned that details of the other Tertiary intrusions in the range show considerable variation. Only general relations of the composite igneous history are presented here, for the purpose of illustrating overall petrogenetic complexities. Three main intrusive phases are considered in their order of appearance. Figure 6 shows the general distribution of these phases. Table 5, on page 56, gives some chemical data on the main phase and deuterically altered rocks.

Pyroxene-diorite phase. — These rocks occur mostly in the northwestern part of the pluton. Megascopically, the diorite is mesocratic, medium-grained, and relatively homogeneous. In thin section, it generally has a hypidiomorphic granular texture.

The diorites have the following modal ranges (based on 18 samples):

Mineral	Range (percent)	Average (percent)
Plagioclase	45.0 - 75	66.5
Hornblende	<5.0 - 15	7.0
Pyroxene	4.0 - 15	6.4
Biotite	1.0 - 10	5.7
K-feldspar	1.5 - 17	4.6
Quartz	2.5 - 10	4.5

Accessory minerals are rutile, apatite, sphene, and magnetite. Secondary minerals are pistacite, clinozoisite, zoisite, pennine, clinochlore, sericite, and actinolite.

Plagioclase averages An_{50}. Euhedral oscillatory and normal zoning are common. The maximum zoning range noted is $An_{60} > An_{28}$. Resorption of plagioclase has produced corroded cores embayed and surrounded by more sodic plagioclase. This phenomenon is termed "patchy zoning" by Vance (1961b). Minor pistacite and clinozoisite formed as a result of this decalcification. The plagioclase commonly is poikilitic, containing inclusions of pyroxene, hornblende, and quartz. Rare vitric inclusions (microplakite) are found only in anorthite-rich cores. Vance (1961b) felt that these inclusions represent melt trapped in the cores after corrosion.

Quartz and K-feldspar are present both as phaneritic crystals and as subhedral to anhedral coarser grained interstitial material. Both have incipiently replaced plagioclase. Antiperthitic intergrowths are common. Locally, K-feldspar crystallization has outlasted that of quartz, as indicated by replacement of the latter by the former.

Hornblende most commonly has the pleochroic formula Z = Y>X, with Z = brownish-green, Y = greenish-brown, and X = light tan. Much of the hornblende has either been altered to actinolite or biotitized, resulting in the segregation of sphene and pistacite.

Most of the biotite is reddish-brown (Z) and occurs as fine-grained mats. Relics of primary, dark-brown (Z) biotite commonly occur in the cores of the fine-grained mats. The reddish-brown biotite appears to have resulted from recrystallization of the primary biotite during contact metamorphism associated with the intrusion of the main-phase quartz diorite.

Both subhedral hypersthene and anhedral diopsidic pyroxene are found in these rocks. All stages of uralitization occur, ranging from unaltered pyroxene through secondary actinolitic hornblende surrounding small pyroxene relics and finally to large masses of fibrous actinolite, without pyroxene remnants, that appear to be pseudomorphic after pyroxene.

Minor later altering of the mafic minerals to clinochlore and pennine has occurred.

The pyroxene diorite rocks were intruded by the main-phase quartz diorite. Intrusive contacts showing this relation are well exposed. Further evidence, indicating that the pyroxene diorite was a solid mass prior to being intruded by the quartz diorite, is found near the southeast corner of the batholith in the Holden quadrangle. Here the diorite was sheared by movement along a high-angle fault. Microscopic evidence of this deformation includes cracked plagioclase phenocrysts filled with quartz mortar. The deformed rocks are cut by undeformed quartz diorite dikes that can be traced back to the main-phase mass.

Main intrusive phase. — The main-phase quartz diorite is massive, light colored, and medium grained. On the whole, it is homogeneous except for the ubiquitous occurrence of mesocratic dioritic inclusions. As in the diorite, the overall texture is hypidiomorphic granular.

The modal average and range of 33 specimens are tabulated below:

Mineral	Range (percent)	Average (percent)
Plagioclase	45 - 70	59.8
Quartz	10 - 25	16.5
Biotite	< 1 - 20	7.6
Hornblende	< 1 - 15	5.4
K-feldspar	2 - 20	5.5
Pyroxene	< 1 - 10	2.3

Accessory minerals are apatite, tourmaline, sphene, zircon, pyrite, and magnetite. Secondary minerals are calcite, pistacite, clinozoisite, pennine, clinochlore, sericite, limonite, kaolin, and actinolite.

Plagioclase is coarse grained and euhedral to anhedral. Its composition ranges from An_{60} to An_{35}, averaging An_{44}. Late decalcification, with the attendant formation of pistacite, is common. Sericitization is minor. Strongly developed euhedral to subhedral normal and oscillatory zoning are characteristic. Synneusis twins are also common. Patchy zoning, consisting of rectangular patches of sodic plagioclase in optical continuity with the crystal rim, has affected about 30 percent of the total plagioclase in the rock. Late partial replacement of plagioclase by K-feldspar and quartz is ubiquitous. Locally, antiperthitic inclusions were noted in plagioclase. Quartz is mostly interstitial and locally has replaced plagioclase. Reddish-brown biotite is both primary and, locally, derived from hornblende. Prehnite commonly is present within biotite along its cleavage. Partial alteration of biotite to clinochlore is ubiquitous. Late hydrothermal alteration to pennine is more localized. Greenish-brown hornblende (Z) has been partially biotitized, possibly contemporaneously with the formation of the secondary K-feldspar. Minor development of pistacite appears related to biotitization of hornblende. Incipient alteration of hornblende to actinolite has occurred. Clinopyroxene has an extinction angle of 45°. Hypersthene is rare. Uralitization of both pyroxenes to actinolitic hornblende is a common retrogressive feature.

The occurrence of rare granodiorite near the margins of the intrusion appears to be due primarily to deuteric replacement of plagioclase by K-feldspar. In a few outcrops, however, granodiorite intrudes the quartz diorite, indicating local magmatic differentiation. In these rocks plagioclase volume (50 percent) is slightly more sodic, ranging from An_{53} to An_{25} and averaging An_{40}. Most of the K-feldspar volume (25 percent) is orthoclase with an average $2V_x$ of 40°. Ford (1959) reported minor anorthoclase in some of the Miners Ridge rocks, but I failed to find it in the pluton to the north. Micropegmatite is more widespread in the granodiorite than in the older quartz diorites. The remaining minerals (quartz, mafics, etc.) occur in a manner similar to that of those in the quartz diorites.

Deuterically altered phase. — Late-stage, acidic differentiates have invaded the earlier intrusive rocks in many areas of the pluton. In the northern part of the batholith, these rocks are relatively rare, occurring mostly as dikelike masses cutting the quartz diorite. In the southern part of the pluton, however, these acidic rocks are more abundant. On

Miners Ridge and Fortress Mountain in the Holden quadrangle, the main-phase quartz diorites have been invaded and deuterically altered by potassium- and silica-rich solutions, presumed to have been residual magmatic volatiles (Grant, 1966). This introduced material was locally of sufficient quantity to cause mobilization of the altered quartz diorite, resulting in small intrusive plugs of quartz monzonite and granite.

These plugs occur, without exception, near the contact of the pluton, particularly at the point of intersection of northeast-trending en echelon shears in the main-phase quartz diorite and northwest-trending overturned anticlines in the roof pendant metamorphic rocks. These structural intersections are thought to have created zones of reduced pressure during a late magmatic stage. It is possible that concentrations of residual potassium and silica from the magma, under high, confining pressure, migrated into such low-pressure zones, provided an avenue to facilitate solutional transfer was present. Figure 7 diagrammatically illustrates these relations.

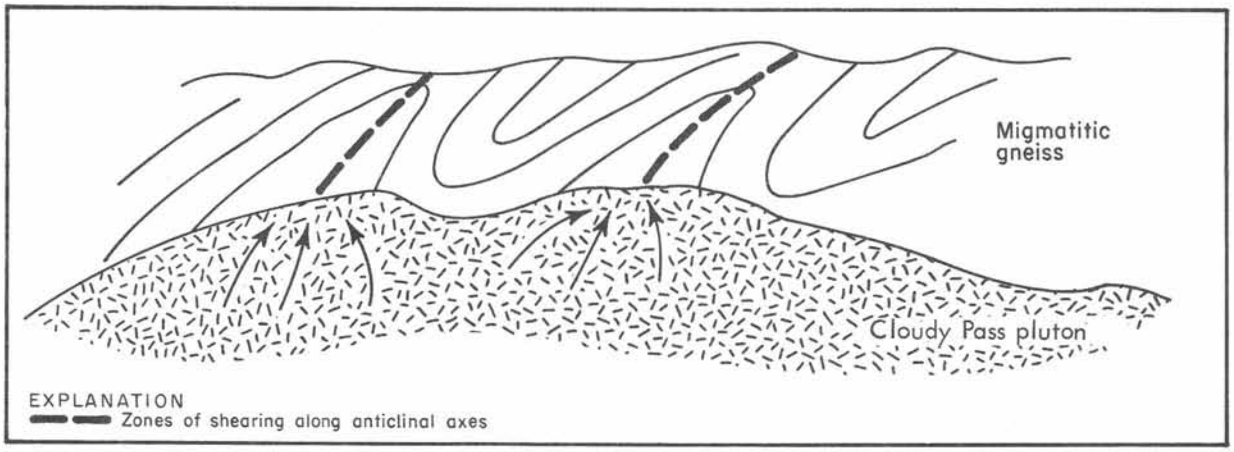

FIGURE 7.—Theorized migration of late residual magmatic volatiles (principally potassium and silica) into zones of weakness along the contact of the plutonic mass. Southwestern contact of the Cloudy Pass pluton.

Figure 8 is a generalized cross section through the Fortress Mountain area showing the distribution of quartz monzonite in the roof pendant overfold zone.

Compositionally, the alkaline rocks on Fortress Mountain range from granite to granodiorite with quartz monzonite predominating. The following modal ranges are based upon 16 samples:

Mineral	Range (percent)	Average (percent)
Plagioclase	2 - 45 (An_{10}-An_{62})	17.5 (An_{26})
K-feldspar (primarily orthoclase)	25 - 65	46.2
Quartz	15 - 30	24.1
Biotite	0 - 5	2.5
Epidote (secondary)	0 - 2	< 1.0

Accessory minerals are apatite, rutile, hornblende, sphene, epidote, tourmaline, magnetite, pyrite, pyrrhotite, molybdenite, and chalcopyrite. Secondary minerals include sericite, chlorite (mostly pennine), limonite, kaolin, siderite, malachite, and azurite.

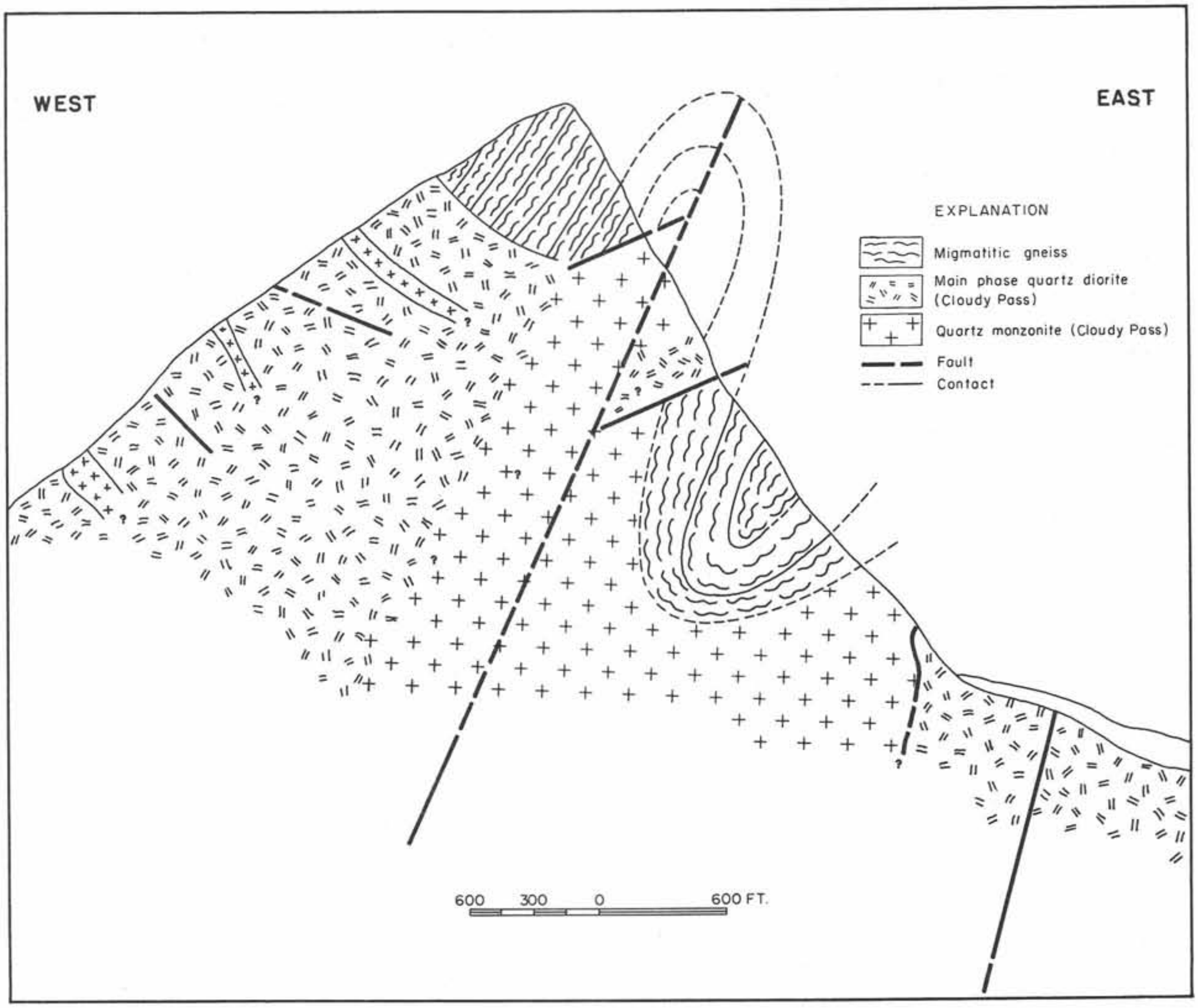

FIGURE 8. — Diagrammatic cross section through Fortress Mountain, eastern Snohomish County, showing the distribution of late quartz monzonite of the Cloudy Pass pluton as related to the overfold structures in the roof pendant metamorphic rocks.

The modes of 26 specimens of alkaline rock collected from the Miners Ridge area are tabulated below. Compositionally, these rocks range from alaskite to granite and quartz monzonite porphyry.

Mineral	Range (percent)	Average (percent)
Plagioclase (present in 12 specimens)	0 - 38 (An_9-An_{44})	15.5 (An_{21})
Quartz	10 - 80	40.4
K-feldspar (present in 21 specimens)	0 - 85	36.7
Biotite (present in 8 specimens	0 - 10	5.4
Muscovite (sericite) (present in 20 specimens)	0 - 55	18.5

Accessory minerals are apatite, zircon, pyrrhotite, pyrite, chalcopyrite, arsenopyrite, sphene, tournaline, hornblende, actinolite, rutile, molybdenite, tennantite, and magnetite. Secondary minerals are alunite, clinochlore, pennine, sericite, epidote, siderite, limonite, malachite, chrysocolla, covellite, and kaolin.

The greatest compositional variation between these rocks is in the quartz content, which averages 24.1 volume percent at Fortress Mountain and 40.4 volume percent at Miners Ridge. The increase in quartz at Miners Ridge is attributed to the occurrence in the center of the granite of a massive quartz plug that permeated the surrounding rocks. No counterpart of this is known in the Fortress Mountain zone.

These granite-quartz monzonite rocks appear to have been derived, through regenerated deuteric processes, from the main-phase quartz diorite. Mineralogical relics of quartz diorite affinity are common. Anorthite-rich (up to An_{62}) cores of relic plagioclase crystals are partially replaced by orthoclase and quartz. This replacement becomes more widespread toward the center of the granite zone.

In many other composite intrusions in the Cascade Range, however, late stage rocks of quartz monzonitic to granitic composition are thought to result from normal magmatitic differentiation or, perhaps, the intrusion of several compositionally different magmas. Each case must be considered separately.

STRUCTURAL ANALYSIS

REGIONAL STRUCTURAL RELATIONS

The regional structural trends in the Washington Cascades are predominantly northwesterly. These trends are most easily distinguished by the axial strikes of the principal faults and folds in the supracrustal rocks of the Central Cascade Province, and the major structures and alignment of rock belts in the metamorphic-plutonic terrain of the North Cascades. The North Cascade structural patterns, being better defined than their counterparts in the Central Cascades, will be discussed in considerable detail. Gross structural patterns in the range are illustrated in Figure 9.

Although the axial belt of migmatitic and granitoid rocks also trends northwestward, the western margin of this zone includes a series of arcuate projections lying at an angle to the dominant trends. A long recognized, much larger counterpart of these divergent structures has been termed by Misch (1960) the "Arc of the Pacific Northwest" (Fig. 10). The plutonic and migmatitic axial belt of the West Cordilleran eugeosyncline trends north to northwest in California; then, at the northern California border, it turns abruptly to the northeast, crossing central and eastern Oregon to the Idaho batholith, where it finally turns back to the northwest and passes through northwestern Washington, including the North Cascades. According to Misch, positioning of this structural arc may have been guided by the western margin of the pre-Cordilleran continental block.

Along the western flank of the North Cascades, the northwest structural controls are well defined by the distribution of the major rock belts. In general, a west-to-east section across the range shows initially slightly to unmetamorphosed middle-to-upper Paleozoic supracrustal rocks in the western foothills, then slates and phyllites, and finally low- and medium-grade isochemically metamorphosed rocks grading into migmatitic and granitoid rocks in the core of the range. This generalized relation has been significantly modified, by faulting and thrusting as well as by the occurrence of "peninsulas" or "embayments" of metamorphic rocks of varying grade that are at least partly surrounded by rocks of contrasting grade. Bryant (1955) mapped one such embayment in the Snowking area west of Cascade Pass. There, medium- and locally high-grade crystalline rocks of the Snowking massif extend northwestward and are bounded on the east by the low-grade part of the Cascade River Schist. Conversely, to the east, Tabor (1961) mapped a southeastward-trending peninsula of low- to medium-grade Cascade River Schist into the granitoid core of the range.

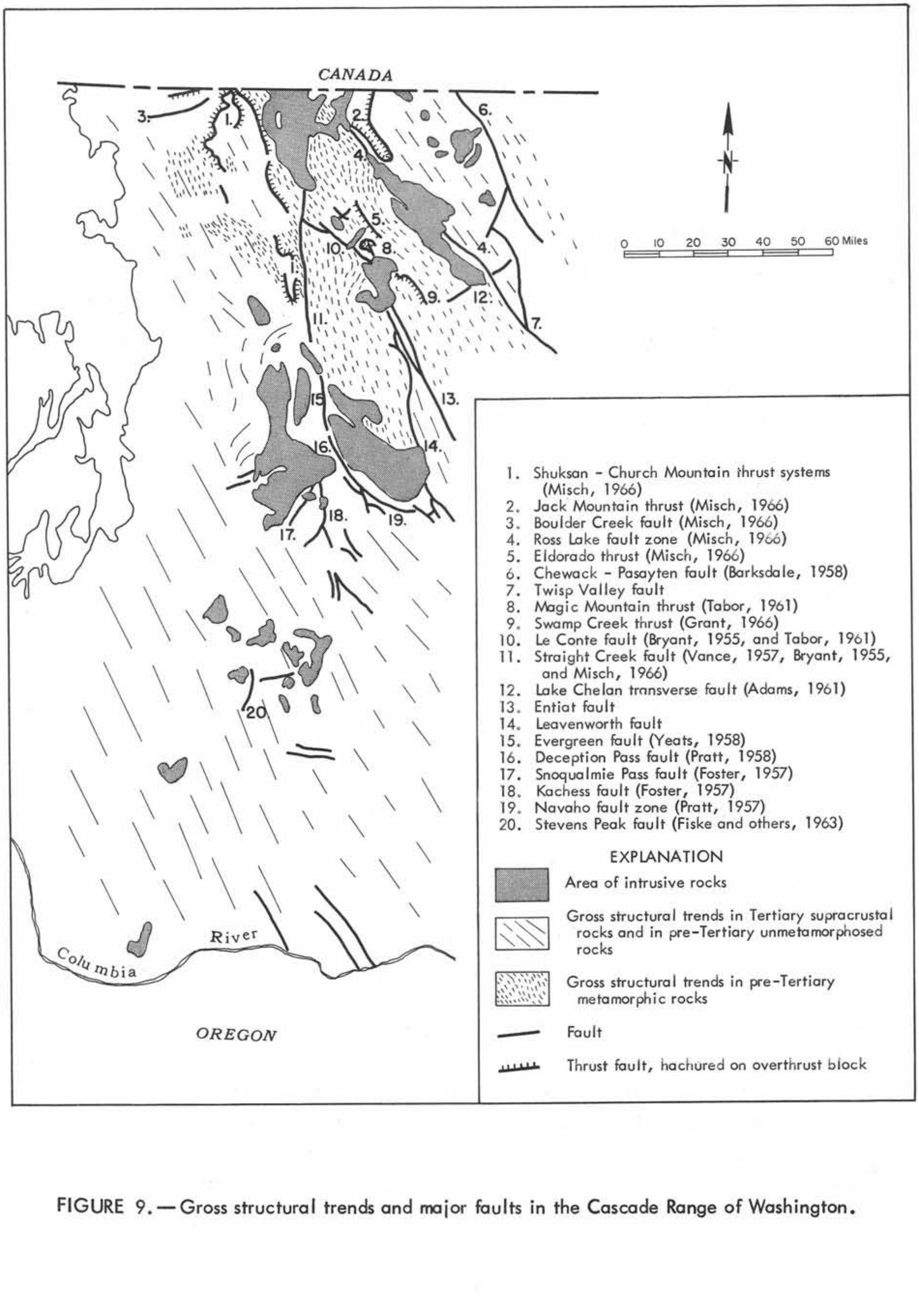

FIGURE 9. — Gross structural trends and major faults in the Cascade Range of Washington.

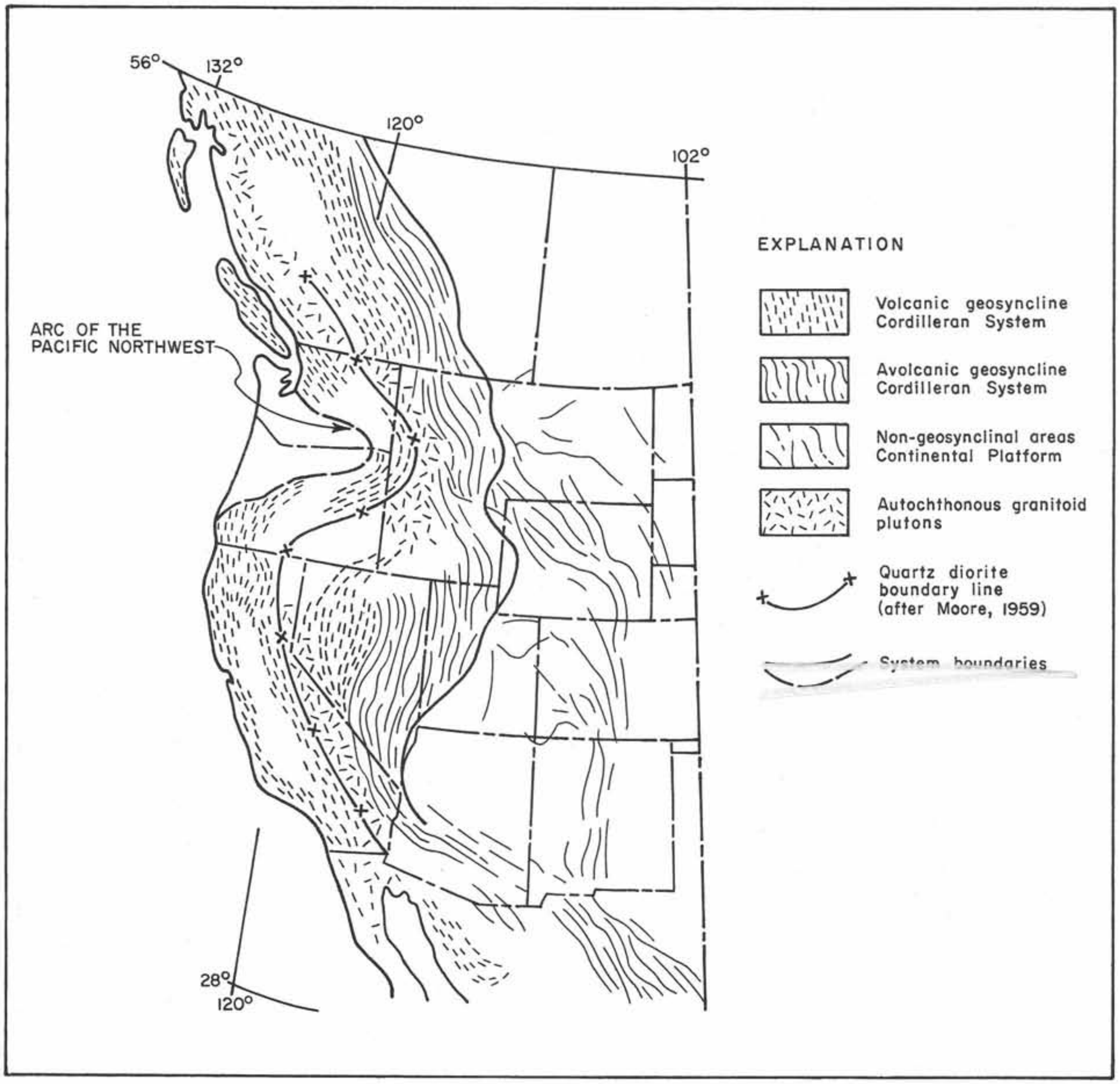

FIGURE 10. — Sketch map of the regional structural patterns in the Western Cordillera of a part of North America showing the Arc of the Pacific Northwest. (After Misch, unpublished data.)

In contrast to those embayments paralleling the regional trends is a series of arcuate transverse structures, resembling a reverse "S" (Ƨ), which Misch (oral communication) has termed re-entrants. Near the Canadian border, Misch found that the major structural trends in the range swing from northwest to northeast and finally back to north to merge with the structural elements on the east side of the British Columbia Coast Range. Farther south, in the Dome Peak area, 10 miles northeast of Glacier Peak, another re-entrant structure has been mapped (Grant, 1966). This structure, informally named the Downey Mountain re-entrant, projects isochemical rocks eastward into the migmatitic-granitoid core. This re-entrant could represent a minor structural adjustment occurring during the formation of Misch's Arc of the Pacific Northwest.

NORTH CASCADES

The structural systems in the North Cascades can be subdivided into three main groups:

Skagit Metamorphism system

Middle Cretaceous orogenic system

Tertiary systems

Structures produced during Skagit metamorphism have delineated the major rock belts in the metamorphic core of the range. In particular, basement rocks occur in a series of anticlinal belts that, for the most most part, are fault bounded, and in some instances are overthrust to the northeast. Imbrication in these thrust zones is common. Evidence strongly suggests that thrusting was synchronous with the late stages of Skagit metamorphism. This inference is based upon several observations:

(a) The structures are fully recrystallized

(b) Adjacent to the thrusts, the tectonized rocks at some places were retrogressively metamorphosed, commonly in greenschist facies

(c) This retrogressive metamorphism appears synchronous with late Skagit low-grade recrystallization, which has occurred in much of the area south of Cascade Pass

Paracrystalline structures within the Skagit Suite are varied. In the isochemical rocks, sub-isoclinal folding is common. Disharmonic fold patterns reflect the differences in competence in areas where heterogeneity of rock units is marked. Near the southwestern arcuate elbow of the Downey Mountain re-entrant, tight folding could reflect structural adjustment during the formation of the re-entrant. Planar schistosity is most strongly developed in the schists and amphibolites. Much of the b-lineation in the schists consists of minute overturned isoclinal folds of s. Later deformation has produced incipient s_2 shears. There are also more widely spaced shears, some showing minor displacement, which appear to be associated with regional metamorphism.

Within the migmatitic and more particularly the homogeneous granitoid gneisses, megascopic structures are not so easily recognized as those in the isochemical rocks due to the absence of well-developed planar schistosity. Continued post-kinematic granitization and local mobilization, coupled in some areas with Tertiary contact metamorphism, have obscured and, in places, obliterated many of the earlier structures. Local nebulitic remnants of tight folds are common in the gneiss complex.

Misch (1966) has discussed the major orogeny occurring in the North Cascades in middle to early Late Cretaceous time. In the northwestern Cascades, two large thrusts, the Shuksan and the Church Mountain, best define the magnitude of this orogenic cycle. East of the crystalline core of the range, the steep Ross Lake fault zone, reverse in part, appears to represent a major strike-slip dislocation zone. Thrusting of moderate magnitude has issued from the main fault zone.

The western thrust belt involves the overthrusting of phyllite and greenschist of the Shuksan Metamorphic Suite over the Paleozoic Chilliwack Group (Shuksan thrust), and the Chilliwack Group over autochthonous Mesozoic rocks (Church Mountain thrust). The root zone of the Shuksan thrust is exposed at a number of places,such as near Twin Lakes, north of Mount Baker. There, the thrust zone is near vertical and contains tectonic slivers of basement crystallines and serpentinized ultramafic rocks. West of the root zone the thrust flattens rapidly. Numerous klippen are preserved, resting on imbricated lower plate rocks. The Church Mountain thrust truncates Mesozoic footwall units and, in part, Paleozoic hanging wall stratigraphic units. In contrast to the Shuksan thrust, severe imbrication and penetrative deformation are less intense in the Church Mountain thrust zone. The map distribution of both these structural units is controlled mainly by Tertiary folding of the thrust planes, resulting in window-like exposures of the lower plate strata.

Figure 11 (after Misch, 1966) illustrates the regional structural setting of the middle Cretaceous orogenic system. West of the crystalline core, the direction of yielding was to the west, whereas easterly yielding characterized the direction of overthrusting east of the crystalline core. Thus the structural parting line of the two-sided but asymmetric orogenic system appears to roughly parallel the axis of the Skagit crystalline belt.

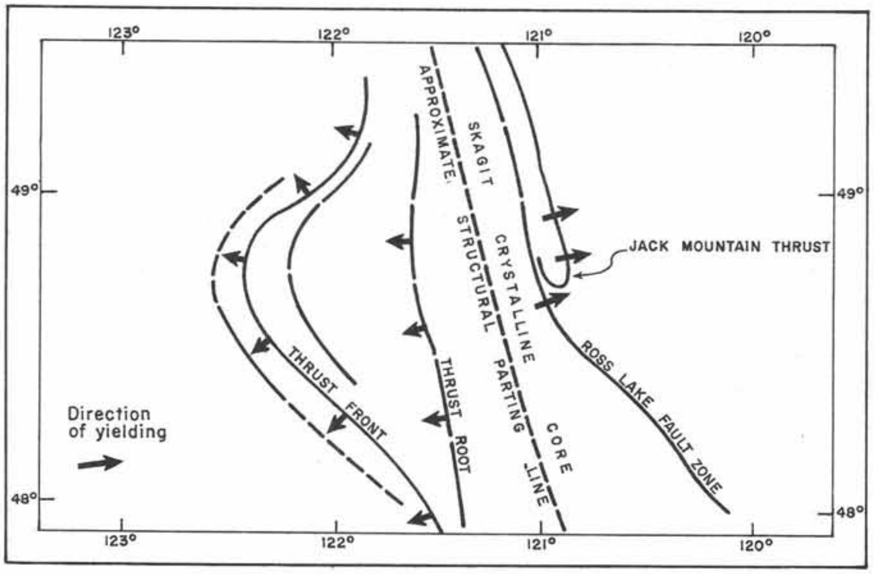

FIGURE 11. — Diagram showing interpretation of the regional structural setting of the mid-Cretaceous orogenic system in the North Cascades. (After Misch, 1966.)

These major overthrusts preceded, by a short time, the start of the Late Cretaceous-Tertiary period of granite evolution in the range. Perhaps the thrusting was triggered by a rising magma front in the metamorphic core. As this front rose, the pre-existing block was displaced along its margin, yielding both to the east and to the west. However, Misch (1966) feels that the Late Cretaceous-Tertiary intrusive activity was not related to the Cretaceous orogeny.

The various Tertiary structural episodes are primarily responsible for the present distribution of the major rock units in the North Cascades. Most significant was an early Eocene orogeny of moderate intensity that was responsible for widespread folding and faulting. In particular, the north-trending Straight Creek fault (Fig. 9, p. 35) constitutes a tectonic boundary between the Shuksan Metamorphic Suite to the west and the Skagit Suite to the east. In the southeastern part of the North Cascade Province, Willis (1950, 1953) mapped two major faults that bound the Chiwaukum graben of folded Swauk strata. Here, faulting is thought to be related to the Eocene deformational period. The western tectonic boundary of the upthrown Mount Stuart block possibly could be a southern extension of the Straight Creek fault, although direct evidence is lacking. It is presumed, however, that this fault system is roughly synchronous with Eocene deformation.

Post-early Eocene deformation in the North Cascades was relatively mild. Gentle folding and local block faulting of the later Tertiary supracrustal rocks have occurred. Large open folds in the crystalline rocks of the North Cascade core might well have been a product of one of these mild middle-late Tertiary orogenic pulses. In general, the intensity of this later Tertiary deformation was much weaker in the North Cascades than in the Central Cascades. Of course, one must consider the fragmentary preserved record of Tertiary rocks to the north as opposed to the thick sequential sections to the south, where the deformational record is more complete, allowing a relatively detailed accounting of the numerous orogenic periods of deformation.

CENTRAL CASCADES

With the exception of the tectonic Easton Schist belt and in the southern extension of Misch's Nooksack Group, pre-latest Cretaceous structures are not exposed in the Central Cascade Province.

Rocks in the northern part of the province have been subjected to the most intense deformation. The oldest rocks, those of the Swauk Late Cretaceous-Paleocene Formation, have been tightly folded and, in some instances, faulted. Both

Ellis (1959), in the Dutch Miller Gap area, and Smith (1904), in the southwestern part of the Mount Stuart area, mapped these fold patterns. West of the folded Swauk belt, across the imbricate Easton Schist belt, volcanic rocks of the upper Eocene Naches Formation have been steeply folded and, locally, overfolded. This deformational cycle represents the most intense of the various known Central Cascade Tertiary periods of deformation and poses an interesting problem in structural correlation. The Swauk Formation was deformed during the early Eocene orogeny, which, in the North Cascades, was the most intense of the various Tertiary deformational episodes. In the Central Cascades, however, the early Eocene orogeny was relatively mild as compared with the later deformation affecting the Naches rocks. In addition, the overfolding in the volcanic rocks had no counterpart in the adjacent Swauk belt. In fact there are few data to indicate that the Swauk rocks were much affected by this later orogeny. It appears that the intense deformation occurring in post-Naches time was restricted to a narrow belt within the core of the northern part of the Central Cascade Province. As this zone is directly adjacent to the previously imbricated Easton Schist belt on the east, it could reflect a selective deformational response in terms of recurrent movements along the Easton structural belt.

Several episodes of mild Tertiary deformation have repeatedly folded, faulted, downwarped, and uplifted the Tertiary rocks. In general, all these cycles produced weak structures paralleling the regional northwesterly trends. At a few localities, northeast-trending faults break the monotony of the northwest grain. These structures are believed to be tensional breaks as an adjustment response to the predominantly compressional stresses that were typical of these Tertiary crustal movements.

Commencing in probable middle Pliocene time, the ancestral Cascades were subjected to epeirogenic upwarping on a north-south axis, plunging gently south. The north-south axis of this epeirogenic movement diverges from the older northwesterly structural trends by approximately 40°. This divergence represents a significant departure from the earlier stress patterns. Late Cenozoic block faulting might have been an adjustment of the relatively rigid crystalline core of the range and may have helped to determine the locus of activity of the late Pliocene-Pleistocene andesitic volcanism. It is logical to assume that some structural activity must have triggered the volcanism by tapping the underlying magma chambers.

TRANSVERSE STRUCTURAL BELTS

One of the most striking results achieved over eight seasons of mapping and studying the environments for base metal deposition in the Cascades has been the delineation of numerous transverse structural belts (Fig. 12) that strike roughly normal to the predominant northwest trends. Furthermore, most of these transverse belts or "lineaments" pass through many of the important mining districts in the range. Even without field studies, one can easily prepare a prospect-major metal commodity distribution map of the range and connect many of the major districts in generalized east-west to northeast-southwest lines.

The idea of northeast to east-west structural controls for sulfide deposition in the Cascades is not new. Spurr (1901) commented on the importance of the imbricated east-west sheeting system in the distribution of ore deposits in the Monte Cristo district. In the November 17, 1904 issue of the Engineering and Mining Journal, R. H. Stretch noted that "the majority of the mining locations in the Cascades have been made along the contacts of granitic intrusions in an E-W sheeting system." Weaver (1912), in his mapping of the Index mining district, recognized the preponderance of northeast-trending mineralized structures. Until recently, however, no systematic structural analysis of the range was possible due to a lack of accurate geologic control data.

Although the data are far from complete, accumulated evidence now indicates the existence of two definite, three probable, and one or more suspected transverse structural belts. These belts are characterized by en echelon shear and (or) fracture systems transversely traceable across the range for distances up to 70 miles. Indeed, the maximum strike length of these lineaments may well exceed 100 miles, the restricting factor presently being the limitations imposed by lack of detailed geologic mapping. For example, the Glacier Peak structural belt (Fig. 12, No. 3) (discussed later in this section) currently

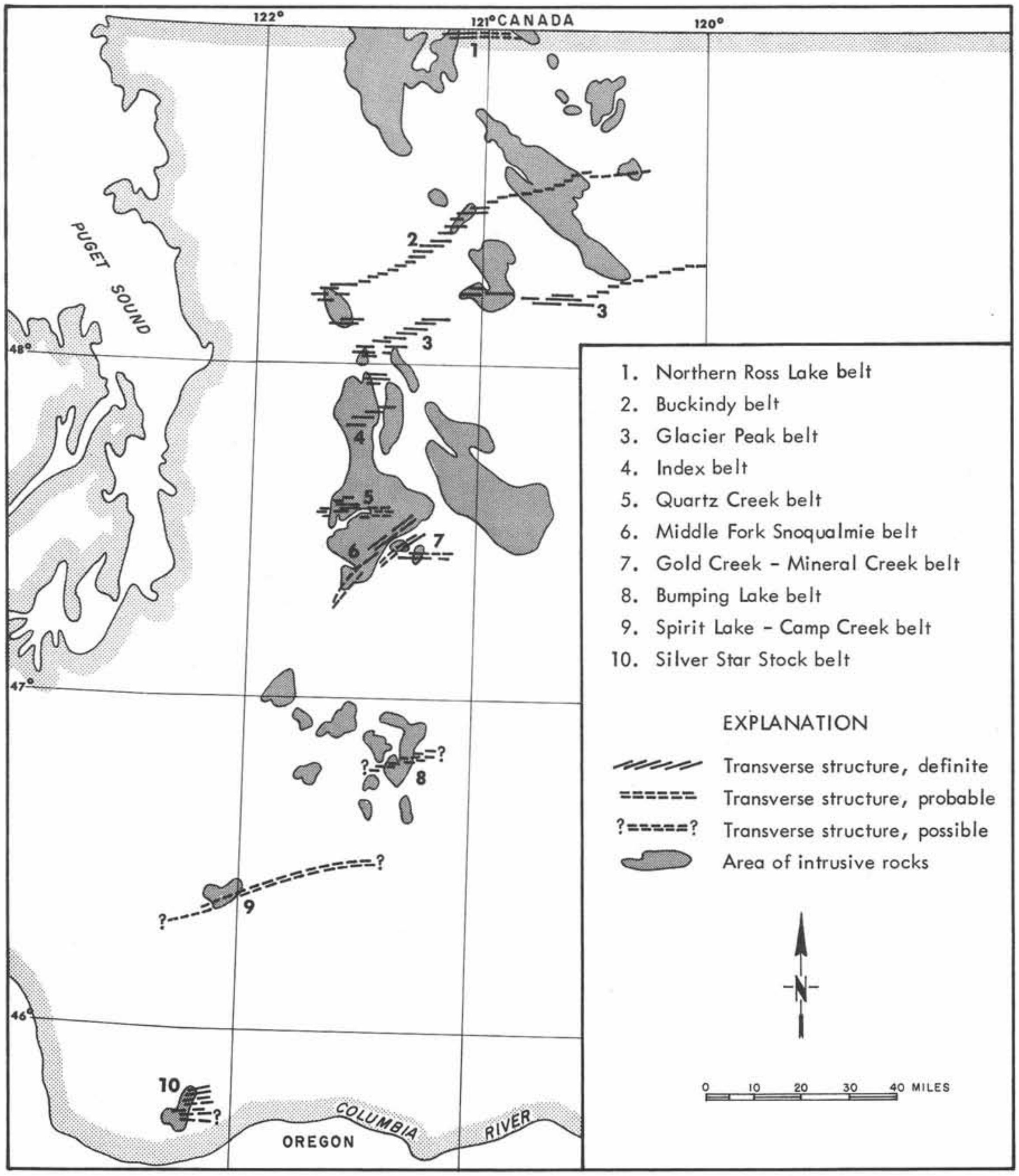

FIGURE 12.— Index map of the known and suspected transverse structural belts in the Cascade Range of Washington.

can be traced from the western edge of the Index district east-northeast through Silver Creek, Red Mountain (Whitechuck River area), Miners Ridge, Holden, Meadow Creek, and finally into the Methow Valley. A further extension of this belt northeast into the Okanogan crystalline block appears likely, although a study of detailed structural relations in that area has not been attempted for this report.

All pre-Pleistocene rocks lying along the strike of these shear belts have been subjected to deformation. The distributed shear and fracture systems are, in many areas, persistent yet subtle in their crosscutting nature. This is probably the reason why many of the earlier workers in the range mapped the strong, obvious north- to northwest-trending structures but failed to delineate or even to recognize the northeast patterns.

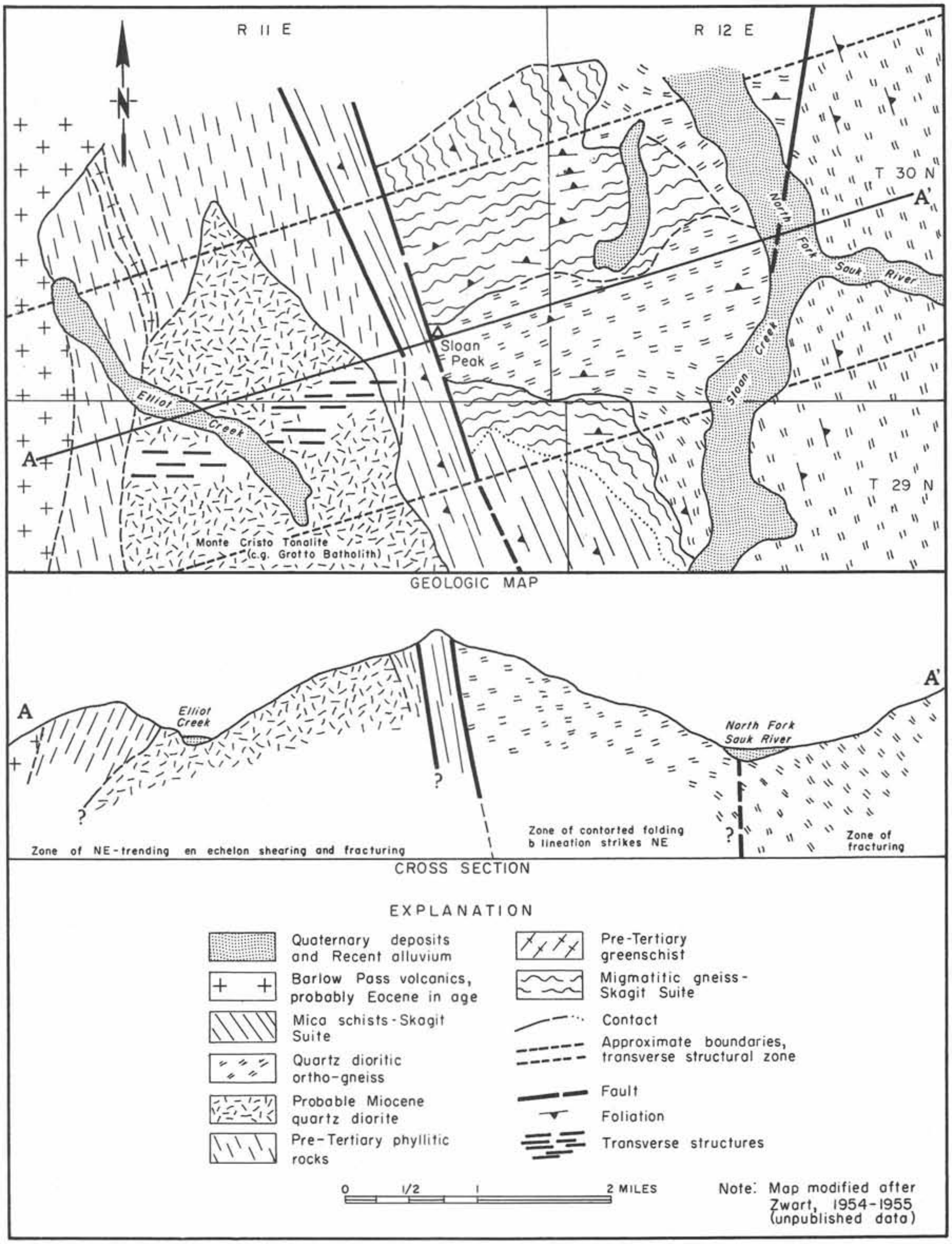

FIGURE 13.—Geologic map and cross section. Transverse structural response along the Glacier Peak structure, Sloan Peak area.

These deformational belts are believed to be relatively deep-seated in origin. In one area, on the southeastern slope of Sloan Peak, in the North Cascades, the Glacier Peak lineament passes through an upthrown horstlike block of pre-Tertiary migmatitic gneiss and schist. This structural block is thought to have been elevated at a relatively late time in the

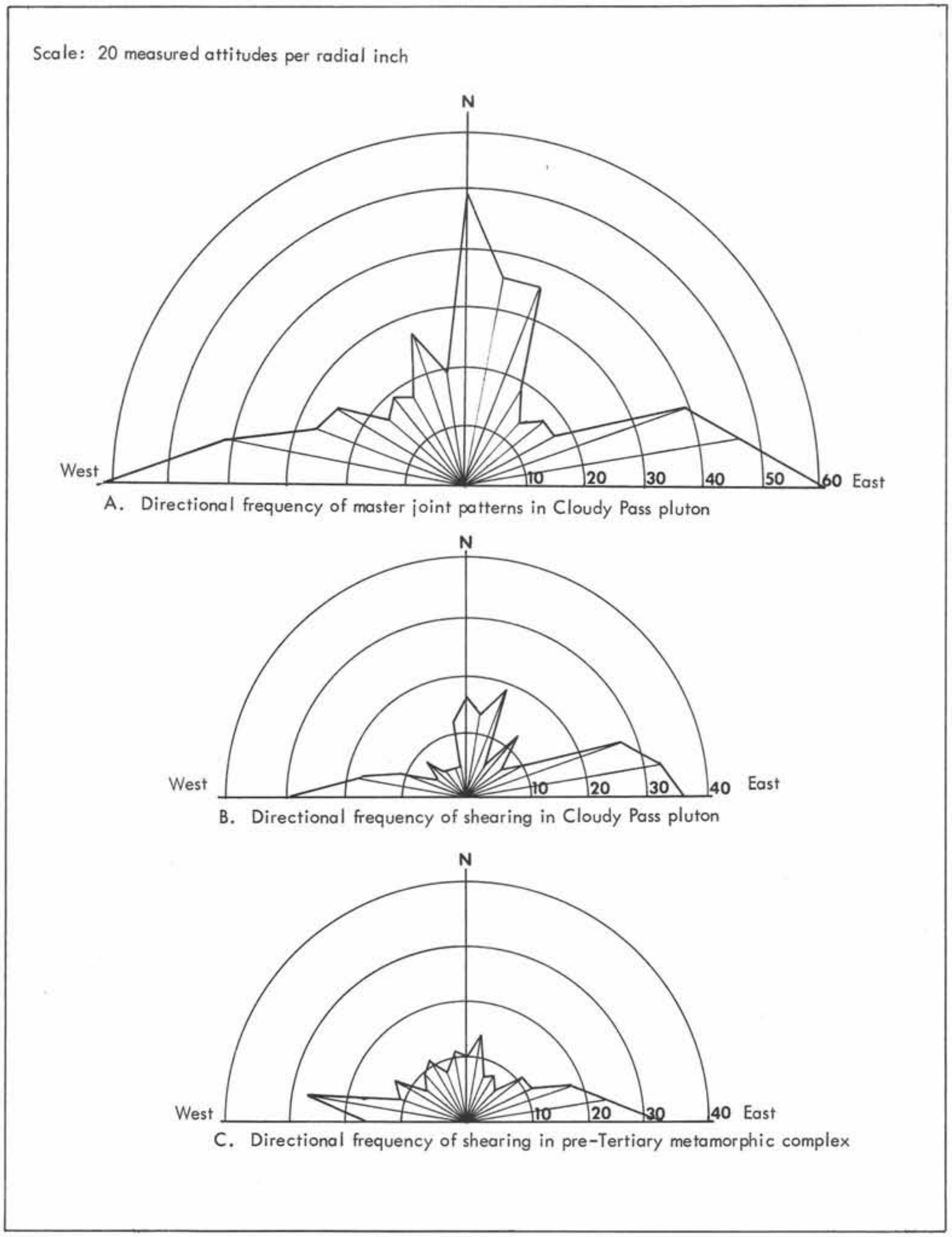

FIGURE 14.—Strike diagram showing the directional frequency of master jointing and shearing in intrusive and metamorphic rocks cut by transverse structures in the Miners Ridge area.

Tertiary period, possibly by faulting related to adjustment of the crystalline core during the Pliocene uparching of the range. On the western side of this fault block the Tertiary supracrustal rocks along the strike of the Glacier Peak structure have been subjected to en echelon shearing and fracturing. In the migmatitic gneiss zone, however, I found no evidence of transverse rupturing; rather, the gneisses along the projected strike of the transverse structural belt have been deformed in a complex series of overfolds, mushroom folds, and various other contortional patterns. This deformed zone is confined to the width of the projected northeast-trending structural belt. Both north and south of the contorted gneisses, the overall structure in the metamorphic complex appears to be a northeastward-dipping homocline with minor folding superimposed. These relations suggest that structural response was disharmonic in a vertical plane during the period of movement along the

Glacier Peak structure. The higher level supracrustal rocks yielded by rupture, whereas the lower level rocks, perhaps situated in an environment of relatively high temperature and pressure related to the period of Tertiary granitic evolution, yielded plastically. These suggestions, of course, are highly conjectural, but possibly do shed some light on the general mechanics of these transverse structural systems. Figure 13 shows the general relations of this disharmonic structural response.

In the crystalline core of the North Cascades, the structural response of the various heterogeneous rock units to these transverse belts can be studied in detail. Shearing and fracturing in the pre-Tertiary metamorphic rocks do not follow any particularly uniform patterns. This problem is compounded because the pre-Tertiary rocks have been subjected to various older deformational episodes. The marked heterogeneity of lithologies within the metamorphic complex adds further complexity to the fracture patterns because of their disharmonic response to stress. For example, northeast of Miners Ridge, in the migmatitic gneiss complex containing intercalated schist and amphibolite layers, the variability of rock competence is clearly reflected by the rapid changes in the fracture patterns. The relatively homogeneous granitoid gneiss exhibits a strong parallelism of northeast-trending structures, but these structures, upon entering the adjacent heterogeneous isochemical layers, become ill-defined and commonly horsetail into a nondescript pattern.

Shearing and fracturing in the post-metamorphic intrusive rocks generally follow a more definitive pattern. In several of the Tertiary plutons, where cut by these transverse structural belts, a marked similarity of joint and shear patterns leads to some theoretical considerations as to the stress mechanics of the transverse systems. The following sequence of structural events is suggested:

(1) The emplacement of the plutons along a general north to northwest axis.

(2) Following the solidification along the periphery of the igneous body, a slight updoming of the mass, possibly caused by pulsating magmatic activity in the unconsolidated core, caused master jointing in a predominantly north-south direction and a complimentary east-west trending tensional system. Figure 14 shows the directional frequency of the master joint patterns, based upon 510 measurements over 6 square miles of the southern part of the Cloudy Pass pluton. The strong north-south- and east-west-trending patterns are apparent.

(3) These master sets of distributed north-south and east-west joints had an important stress-directing influence during the period of structural activity along the transverse deformational zones. In the southern part of the Cloudy Pass pluton the accumulation of structural data strongly suggests that the original master joint sets directed the northeast-trending transverse stresses into the pre-existing fracture pattern (Fig. 14). Figure 15 illustrates the hypothetical major stress directions and the directions of yielding. Maximum displacement measured in this section of the Cloudy Pass pluton was less than 5 feet along the east-west sheeting system. North-south displacement was not observed.

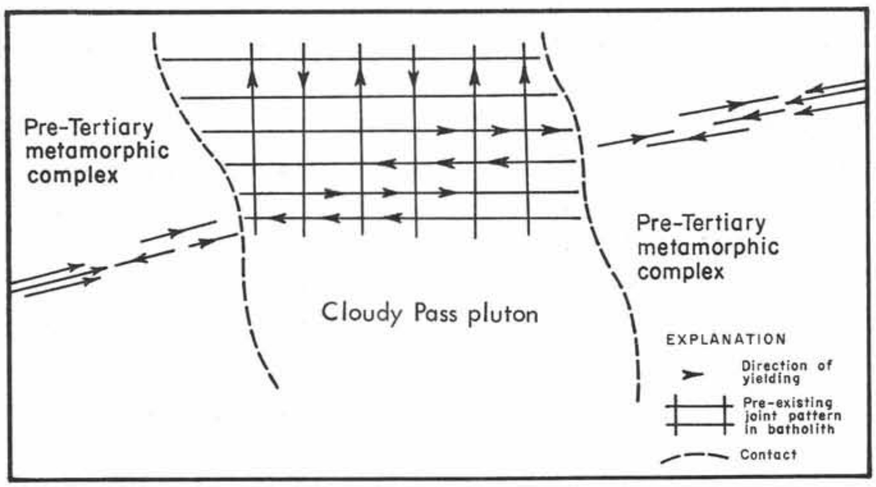

FIGURE 15. — Possible joint pattern influence on directions of yielding in transverse structural belt. Southwestern part of Cloudy Pass pluton.

These transverse structural belts pose an interesting problem as to their origin because, in general, they cut the regional grain of the Cascade system. Several hypotheses are considered:

The belts could be a result of tensional adjustment to the strong northwest-trending movement zones. If this is the case, however, one would expect a more uniform distribution of transverse structures rather than their confinement to specific belts.

The belts could represent a high-level expression of some ancient, deep-seated movement zone. Of course there is no evidence to support this possibility, but large rifts are known to exist in various continental basement blocks. It would be interesting to project some of these transverse zones eastward (through detailed field examinations) to determine whether there is any direct, or even indirect, relation to known major transverse dislocations such as the Osborne fault system, in northern Idaho.

The northeast-trending re-entrant structures, previously described on page 36, may have structurally influenced the positioning of the transverse belts. In the North Cascades the two transverse belts of greatest magnitude are those of the Glacier Peak and Buckindy structures (Fig. 12, on p. 40). Midway between these belts there has been mapped (Grant, 1966) a large re-entrant structure in which the predominant northwest trends in the crystalline rocks swing from northwest through north to east for several miles before arcing back to the northwest. The overall trends of the reverse part of the re-entrant structure parallel the trends of the transverse belts. Misch (oral communication, 1959) believes that these re-entrant structures could represent minor deep-seated fluctuations in the overall geosynclinal stress system. These, in turn, could have created a zone of weakness in the crust that might have influenced later transverse deformation.

Cascade Transverse Structural Belts

A brief description of the major transverse structures delineated in this paper follows. Locations and magnitude of these belts are shown on Figure 12, on page 40. The reader is cautioned that detailed structural mapping in the range is far from complete. Other transverse structural belts may exist, as well as extensions of the presently known or suspected zones.

Northern Ross Lake belt. — This transverse belt has been delineated for only a short distance in the Ross Lake area, but regional evidence suggests its easterly continuation toward the upper Pasayten drainages along the Canadian border. This suggestion is partly corroborated by pronounced east-west sheeting that cuts several small Tertiary igneous stocks intruding along a general east-west line. In the Silver Creek valley, west of Ross Lake, the zone is best exposed by northeast-trending structural warping of the Oligocene Skagit Volcanics (named by Daly, 1912) and distributed northeast fracturing in both the volcanics and the subjacent, younger Perry Creek intrusive. Coincident with this structural belt is the existence of promising molybdenum and copper mineralization in a high potassium and silica alteration environment (see Descriptive Area Studies, on page 67).

Buckindy structural belt. — This zone, named after Mount Buckindy, through which this structural belt passes, is the second largest transverse belt known to exist in the range. Although data are incomplete, the western end of the structure may pass through the Darrington mining district, situated just south of the logging community of Darrington. Northeast from Darrington, little is known about the belt until it cuts through the Mount Buckindy massif. Here it is present as a more-than-1-mile-wide belt of en echelon shears and joints, mostly trending east-west. Sulfide mineralization is ubiquitous in this part of the structure. Northeast from Mount Buckindy, across the South Fork of the Cascade River, strong, distributed shearing characterizes the zone. Misch (1966) found that the Cascade Pass Quartz Diorite pluton follows a northeast-trending fracture system as did Tertiary andesite dikes predating the Cascade Pass intrusion. The emplacement of the Cascade Pass pluton may have been, in part, structurally controlled by the northeast structures. Northeast from Cascade Pass, the Buckindy structure passes through the Skagit Queen and upper Thunder Creek mining districts. A minor divergence of this structure is possible northeast of Cascade Pass, where a more eastward-trending shearing crosscuts the Horseshoe Basin mining district.

From Thunder Creek the belt appears to trend northeast toward the Harts Pass mining district. Structural data in this area are incomplete, so this projection is, at best, speculative.

Glacier Peak structural belt.—The Glacier Peak structure is the largest of the transverse belts now known to exist in the range. The exposed western end of the belt passes through the Vesper Peak-Sultan Basin districts. Here the structure is best characterized by sheet jointing and minor shearing in the intrusive rocks. A southerly, possibly related, counterpart of the main structure cuts through the Index mining district, where Weaver (1912) noted that a majority of the sulfide veins strike to the northeast in an en echelon pattern. From the Sultan Basin area the main belt cuts through the upper reaches of Silver Creek and thence through the Monte Cristo mining district. There, Spurr (1901) noted the northeast parallelism of the imbricated joint system and the principal sulfide veins. From Monte Cristo the Glacier Peak structure strikes northeast toward Glacier Peak, disharmonically affecting the heterogeneous complex of metamorphic rocks as previously described. The Pleistocene volcanic rocks on Glacier Peak are not affected by the transverse structures, thus fixing the upper age limit for this deformation. East of Glacier Peak the main structure cuts the Cloudy Pass pluton, being best exposed in the Miners Ridge area. Here the zone has strongly influenced the positioning of the Miners Ridge copper deposits. Several miles east of Miners Ridge, a late Tertiary high-angle strike slip fault has offset the Glacier Peak structure, displacing the eastern block to the southeast (Fig. 23, on p. 72). From there the structure passes through the Holden mine area and eastward past the Meadow Creek mining district on the east side of Lake Chelan. Just east of the Meadow Creek area, Adams (1961) mapped a major transverse fault paralleling this part of the Glacier Peak structure. Eastward from Adams' area, little is known about the structure, but on a general easterly projection of the belt an east-west sheeting system in the Alder mine area near Twisp, in the Methow Valley, has been mapped by the writer.

Middle Fork Snoqualmie River structural belt.—This zone differs considerably from the northern structural belts, in that the various transverse zones do not appear to be physically connected and they also exhibit a considerable variability in trends.

In the Quartz Creek area, near the west end of the structural zone, east-west-trending en echelon sheeting and shearing in the intrusive rocks are coincident with several mineralized breccia pipes. Bedding attitudes in the overlying volcanics trend northeast in a manner similar to the previously described (on page 36) re-entrant structural warps that occur in the North Cascades.

In the Middle Fork of the Snoqualmie River area, near Goldmeyer Hot Springs, a wide belt of northeast-trending en echelon shears are the principal structural controls for the numerous sulfide occurrences. This transverse zone cuts the batholithic rocks of the Snoqualmie pluton and appears to be a northeasterly extension of a major fault system mapped by Foster (1957, 1960) that cuts the Tertiary volcanics to the south. The transverse structures in the mineralized zones are offset by a complex series of north- to northwest-trending high-angle faults.

Gold Creek-Mineral Creek belt.—East-west-trending joint and shear systems in this area occur principally in a satellitic group of stocks that are probably connected, at depth, to the main mass of the Snoqualmie batholith. Coincident with these transverse structures are large areas of pervasive sulfide mineralization. In the Mineral Creek drainage, several small breccia pipes occur along zones of relatively intense east-west sheeting. Only a few reconnaissance examinations in this area have been made by me, and therefore little can be said concerning the projection and overall magnitude of this shear system.

Possible other transverse belts.—South of the Middle Fork of the Snoqualmie-Gold Creek areas, little detailed structural information is available. Suggestions of the existence of other transverse systems were noted in such areas as the Bumping Lake intrusions east of Mount Rainier, the Camp Creek stock southwest of Randle, the Spirit Lake stock east of Mount St. Helens, and the Silver Star stock in southern Skamania County. Sporadic sulfide occurrences have been reported from all these areas, but, in general, neither the magnitude of the structural ground preparation, wall rock alteration, or the types of sulfide occurrences are indicative of significant potential. However, it must be mentioned that extensive Tertiary cover and lack of fully reliable data from these areas preclude any final evaluation.

STRUCTURAL INTERSECTIONS

The transverse tectonic belts have been shown to be important controlling structures in the spatial distribution of the sulfide deposits. However, most sulfide occurrences are restricted to a few specific localities along these structures.

This fact is particularly evident at Miners Ridge, where the copper deposits are confined to certain parts of the transverse structural zone in spite of the overall similarities in the geologic environment within that area of the Cloudy Pass pluton. This erratic sulfide distributional pattern suggests the presence of other factors which influenced the positioning of these deposits. Structural studies in the Miners Ridge area revealed the existence of several large anticlinal overfolds, overturned to the northeast, in the roof pendant metamorphic rocks several hundred yards north of the main copper deposit area. The axes of these anticlines trend northwest-southeast, paralleling the regional structural grain produced during the Cascade metamorphic cycle. The age of folding is also thought to be synchronous with the Cascade cycle. Although the metamorphic rocks have been eroded from over the principal sulfide deposits occurring in the batholithic rocks, the projected axis of the largest overfold, marked in the gneiss by axial plane shearing, can be shown to trend southeast toward the area of the main deposit. At the point of intersection of the projected fold axis and the northeast-trending en echelon shear system (Fig. 6, on p. 29), the Cloudy Pass intrusive rocks are deuterically altered to quartz monzonite and granite, and they contain disseminated sulfides. This intersection coincides with the area of the principal copper occurrences on Miners Ridge. A less well defined, but apparently similar, structural intersection occurs several thousand yards east of the main deposit. Here, wall rock alteration and sulfide deposition are analogous in overall type, but not in intensity, to the western deposit.

The anticlinal structures in the roof pendant metamorphic rocks are thought to have created zones of reduced pressure during the late magmatic stages of plutonic emplacement. It is possible that concentrations of residual magmatic volatiles (principally potassium- and silica-rich components), under conditions of high confining pressure, migrated into such zones (provided the avenues to facilitate solutional transfer were present). Mason (1958) stated that the pressure of these residual volatiles might be sufficient to inject them along surfaces of weakness into adjacent rocks. The structural couple involving shears in the periphery of the intrusive mass and pre-intrusive folds in the overlying metamorphic rocks could have created a suitable zone of weakness for such injection.

In the Holden mine area, approximately 9 miles east of Miners Ridge, another fold-shear structural couple may have significantly influenced the positioning of the main ore body. For details of this area, the reader is referred to the section of this paper headed "Descriptive Area Studies" (p. 73).

In other Cascade mining districts that are situated along the transverse tectonic belts, preferential structural orientation of the veins to the northeast is common. At many properties, however, the most extensive sulfide mineralization occurs in or adjacent to the intersection of northeast-trending shears and northwest-trending faults.

The importance of structural intersections in ore deposition has been demonstrated in several major metallogenic provinces in the Western Cordillera. The work of Billingsley and Locke (1941) on the regional localization of ore bodies is probably the most comprehensive study to date on this problem. They noted the occurrence of first-magnitude deposits at loci where major orogenic belts are cut by transcurrent faults. McKinstry (1955) stated that studies of this type offer a fruitful field of research even though it is inevitable that such interpretations must be in some degree subjective, involving a certain amount of idealization. This statement, in essence, summarizes the present status of structural understanding in the Cascades. The fundamental patterns have been established, but it is still necessary to fill the "data gaps" with sufficient information to evolve a series of well-founded working hypotheses.

WALL ROCK ALTERATION

GENERAL CONSIDERATIONS

Neuerburg (1958) discussed the various types of wall rock alteration associated with intrusive processes. He made the distinction between hydrothermal and deuteric alteration on the basis of the physical state of the material being altered. Deuteric alteration is considered a type of autometamorphism affecting unconsolidated rocks, the source of the alteration solutions being syngenetically related to the parent igneous mass. This process, according to Neuerburg, has no particular relation to structure. In fact, he states (1958, p. 287) that "geometrically irregular textural variants in deuterically altered rocks may be a result of increased vapor pressure and concentration of mineralizers in local, hermetically sealed volumes of rock." Hydrothermal alteration sensu stricto, again as defined by Neuerburg, generally refers to alteration occurring after full solidification of the affected rocks. This type of alteration is commonly localized along or adjacent to steep fractures.

Using these definitions as a point of departure, it would be appropriate to consider the nature of alteration itself. In essence, alteration is a metamorphic process and thus subject to most of the variables affecting the metamorphic environment. Recent workers, such as Creasy (1959), have attempted to consider alteration types in terms of metamorphic facies. That procedure, however, will not be incorporated in this paper. Eskola's (1920)original concept of metamorphic facies stated that rocks of the same chemical composition are of the same facies if they contain the same basic mineral components. The obvious advantage of this concept is that each zone is defined by a mineral assemblage rather than by a mineralogical linear progression, as was the earlier case in Barrow's (1893, 1912) regional metamorphic scheme. The mineral assemblage concept is multidimensional and takes into consideration pressure/temperature variables. In altered rocks, however, this approach is not fully satisfactory. It is difficult to apply the facies concept to rocks that have been subjected to several stages of alteration, each of which has tended to create a condition of instability in the natural system. Many of the resultant mineral assemblages in an alteration environment depend not only on P/T ratios but also on such factors as the chemistry of the wall rock and of the introduced material. Other variables, such as the partial pressure of water and carbon dioxide, could significantly affect the end products. Therefore, in this paper, alteration types will be referenced by mineral assemblages, but without implication as to the physical environment.

REGIONAL IGNEOUS PETROCHEMICAL ENVIRONMENT

As noted on pages 59 to 63 , the close association between the Late Cretaceous-Tertiary intrusive plutons in the Cascades, their intrusive chemistry, and the periods of sulfide deposition has been well documented. At this point, it is essential (first) to establish the regional petrochemical environment for these intrusions. Using these data as a point of departure, it will then be easier to discuss intelligently the chemical "anomalies" as related to wall rock alteration.

Viewing the Cordilleran system on the whole, Moore (1959) pointed out some interesting variations in the compositions of the intrusive rocks and their geographic distributions. He also reviewed voluminous geologic and chemical data on the intrusions in the western United States, and was able to show fundamental compositional differences between the granitic rocks along the western continental margin and those farther east. To the west, the intrusions are predominantly quartz dioritic-granodioritic in composition, whereas to the east, they are mostly granodioritic and quartz monzonitic. Moore called the line separating these two zones the "quartz diorite boundary line" (Fig. 16). He attributed these contrasting intrusive compositions to crustal compositional variations existing prior to the emplacement of the granitic rocks.

Regardless of the reasons why, the quartz diorite line appears to be a valid compositional boundary. It is roughly coincident with the boundary between the eugeosynclinal and miogeosynclinal parts of the Cordilleran system. Misch (oral communication, 1958) suggests that most of the intrusive masses in the eugeosyncline are autochthonous, having migrated

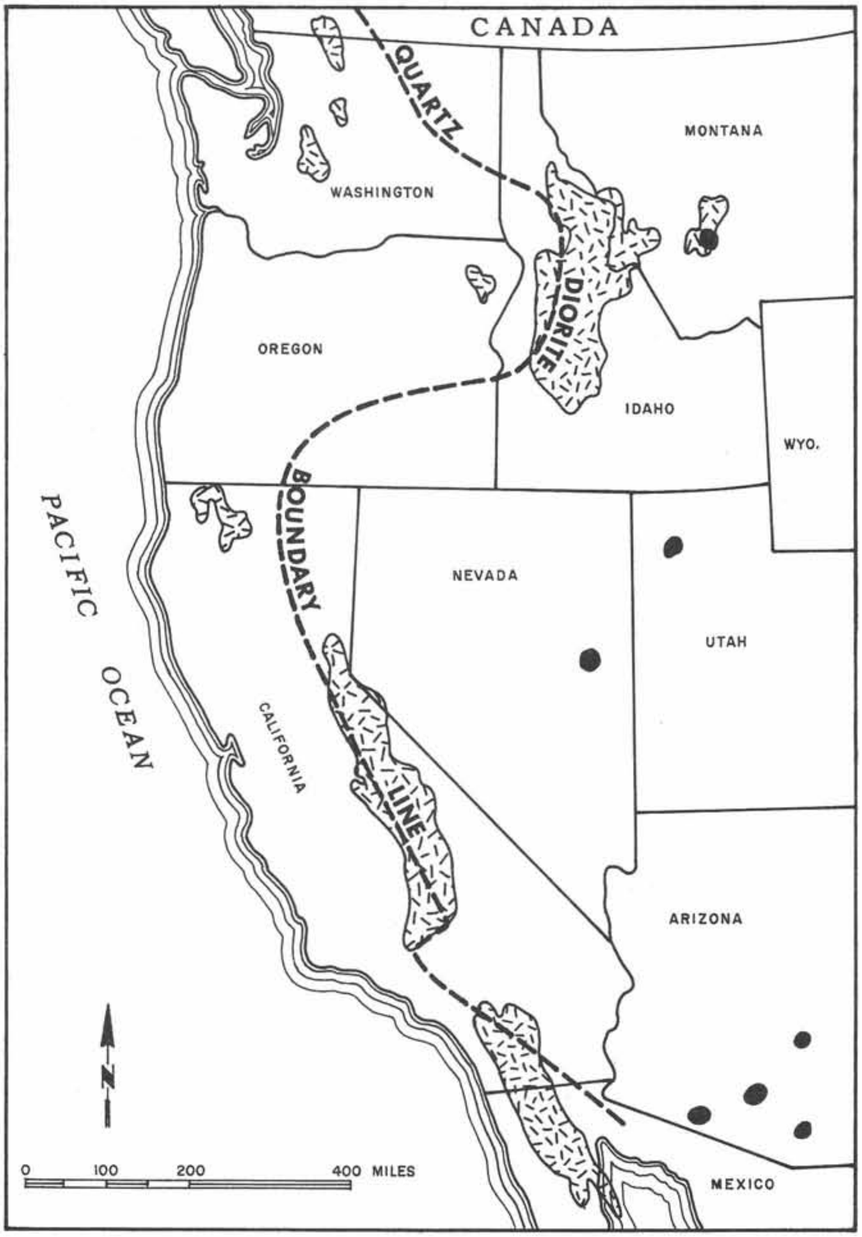

FIGURE 16.—Quartz diorite boundary line (after Moore, 1959) in the Western Cordillera of the United States. Intrusive rocks west of the line are predominantly quartz dioritic. Rocks east of the line are predominantly quartz monzonitic. Black areas represent some of the major copper deposits associated with alkaline rocks.

little distance from their zone of formation. Correspondingly, the miogeosynclinal plutons are considered by Misch to be allochthonous, having migrated some distance in the crust to their present positions. Whether all these plutons were differentially derived from a common parental magma or perhaps were palingenetically derived from contrasting parent crustal material remains as one of the significant problems in North American geology.

Having established the calc-alkaline nature of the intrusive plutons in the Cascade Range, it is interesting to briefly compare the sulfide depositional environments in the Cascades with those in the southwestern United States, east of the quartz diorite line. Many of the major ore deposits in the Southwest, particularly the "porphyry coppers," occur within or are associated with acidic intrusive porphyritic rocks. Their high potassium composition is characterized not only by their average quartz monzonitic composition but also by their typical K-silicate alteration in the copper sulfide zones. Although most of the intrusive rocks in the Cascades are quartz dioritic in composition, many of the copper sulfide deposits occur in the part of the pluton that is more acidic either by late-stage magmatic differentiation or by deuteric alteration in a potassium-rich free silica environment. The similarities between the intrusive rock chemistry and metallization east and west of Moore's line are striking.

DEFINITION OF ALTERATION TYPES IN THE CASCADE ENVIRONMENT

Three major wall rock alteration types, propylitic, quartz-sericite, and biotite-orthoclase, are predominant. Subordinate types, such as clay-sericite, appear to be of no particular significance. Schwartz (1956) stated that, in general, clay minerals form during the early stage of an advancing front of alteration and are commonly converted to sericite as the process continues. In the Cascades the intensity of alteration, particularly in areas of significant sulfide deposition, may have surpassed the earlier clay phase, thus accounting for the general absence of clay alteration. It must be pointed out that most of my research in Cascade alteration types has been restricted to areas where intense, and thus well-defined, alteration processes have occurred. Study of some of the lesser altered areas might reveal substantial clay development.

Propylitization is characteristically a fringe type of alteration, bordering quartz-sericite or biotite-orthoclase types. Some areas have been subjected to ubiquitous, relatively intense propylitization. In others, propylitic alteration is restricted to structures. Minerals characteristic of the propylite zone are epidote (both clinozoisite and pistacite variety), chlorite, calcite, and sericite. Plagioclase is decalcified, commonly, but not in every instance, to albite. Subordinate minerals are quartz, kaolinite, montmorillonite, and green biotite. According to Creasy (1959), the propylitic type of alteration is roughly correlative to the muscovite-chlorite metamorphic subfacies with excess silicon dioxide and carbon dioxide.

In the Cascade deposits, propylitic alteration is the weakest alteration type, commonly forming a transition between the more intensely altered rocks and the unaltered country rock. Around some of the larger zones of disseminated sulfides the propylite halo may extend outward for as much as 1 mile from the deposit.

Quartz-sericite alteration is, by definition, characterized by the mineral assemblage quartz-sericite. Chlorite is a common accessory. This type of alteration occurs generally in an intermediate position between the outer propylite and the inner K-silicate core. While propylitic alteration shows little gain or loss in major cations (as compared with the presumed calc-alkaline igneous parent rock), quartz-sericite shows an extensive gain in silica and potassium and a corresponding loss in aluminum, ferrous iron, magnesium, calcium, and sodium. As with the propylitic type, the quartz-sericite alteration type would be roughly correlative to the muscovite-chlorite metamorphic subfacies.

Argillic alteration, defined mainly by the assemblage clay-sericite, is included under the general quartz-sericite classification. Most workers prefer to establish argillic alteration as an intermediate alteration phase between the propylitic and K-silicate types. In many areas, particularly in the acidic plutons of the southwestern United States, this classification appears valid. In the Cascades, however, as previously pointed out, argillic alteration, particularly with clay, is subordinate and will not be considered further.

The most important of the various alteration types associated with Cascade sulfide deposits is the K-silicate, or biotite-orthoclase, type. It is easily distinguished by the presence of fine-grained secondary biotite and (or) orthoclase. The type of "orthoclase" referred to here is a potassium-rich monoclinic feldspar that has low sodium content. The orthoclase mostly replaces pre-existing plagioclase and (or) quartz. In some instances it occurs with quartz in crosscutting veinlets. Secondary biotite is characteristically present in fine-grained mats, commonly pseudomorphic after ferromagnesian minerals. Secondary quartz is late and occurs in moderate amounts. The earlier rock fabric is partly or wholly destroyed by the secondary minerals. Major cation gains in the orthoclase-biotite type of alteration, as compared with the original wall rock (again assumed to be a calc-alkaline igneous rock), are aluminum and potassium. Significant cation loss of ferrous iron, magnesium, calcium, and sodium has occurred.

Other alteration types, such as silicification, carbonitization, and tourmalinization, are not discussed in detail, as they are fairly self-explanatory. Silicification, because of its relation to some of the molybdenite occurrences in the range, constitutes a fairly important and easily recognizable alteration type.

Figure 17 shows the generalized spatial relations to be found between the principal alteration zones associated with a "typical" Cascade "porphyry copper"-type deposit.

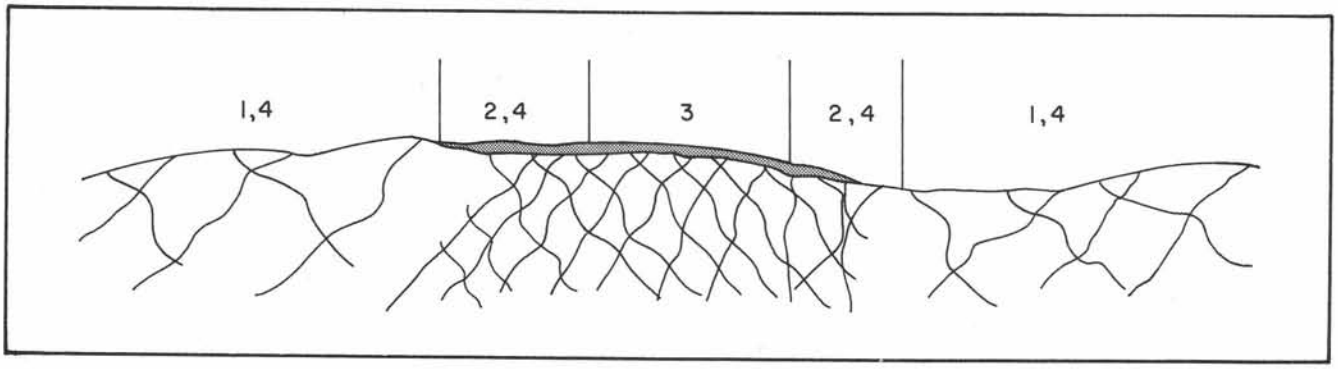

FIGURE 17.—Idealized cross section showing the spatial relations between the principal alteration zones. Black capping over the central zone shows the area of high rock chemical reactivity amenable to rapid supergene alteration.

1. Propylitic—Primary mineral alteration consists of biotite → chlorite
   hornblende → chlorite + epidote
   Principal sulfide—pyrite
   feldspar → sericite + epidote
2. Quartz-sericite—Feldspars are generally altered to sericite. High free silica (quartz). Ferro-magnesium minerals (including chlorite) are generally absent or present only as relicts. This type of alteration may result from either supergene or primary causes. Principal sulfides present are pyrite and chalcopyrite and less common occurrences of pyrrhotite.
3. K-silicate—Primary alteration minerals present are orthoclase and (or) secondary biotite. Earlier rock fabric may be partially preserved, or obliterated by replacement. Principal sulfides present are chalcopyrite with pyrite and (or) pyrrhotite. Molybdenite may occur.
4. Silicification—Quartz introduction. More common alteration environment for molybdenite deposition. All types of sulfides may occur in this zone.

PETROGRAPHIC DESCRIPTIONS

All the alteration systems discussed in this paper have been defined partly, by thin section studies. Of particular significance is the establishment of petrogenetic relations between the various stages of alteration in those areas where alteration has been multicyclic. The important alteration minerals are discussed below.

Potassium Feldspar

K-feldspar is one of the most significant index minerals in the alteration sequence. The critical member of the K-feldspar assemblage is monoclinic orthoclase. It can be most readily distinguished optically by a negative optic angle of less than 50°, in contrast to igneous K-feldspar, which has a considerably higher $2V_{\underline{x}}$. These data are determined by the optic angle curves defined by Tuttle (1952) and later modified by MacKenzie and Smith (1956). Mason (1958) noted that at high temperatures complete solid solution exists between $KAlSi_3O_8$ and $NaAlSi_3O_8$. The more potassic (considerably richer in potassium than sodium) members of the series are called soda-orthoclase and are monoclinic. The more sodic members are called anorthoclase and are triclinic. In this high-temperature environment the potassium and sodium ions are randomly distributed in the framework, producing a relatively homogeneous crystal. With decreasing temperature, ordering occurs, resulting in the formation of potassium-rich and sodium-rich crystals, commonly as perthitic intergrowths.

The later, deuterically formed orthoclase differs texturally from the earlier, igneous K-feldspar. The primary K-feldspar occurs late in the crystallization sequence, both as phaneritic crystals and as subhedral to anhedral interstitial material. Perthitic and antiperthitic intergrowths are common. Also relatively common is the development of micrographitic textures. The later orthoclase in the deuteric environment is characterized by xenoblastic crystals replacing quartz, sericite, and plagioclase, with preference for the last. In more advanced development, orthoclase tends to form porphyroblasts or, where individual crystals have coalesced, glomeroblasts. In other instances, orthoclase and quartz occur as fine-grained matrix material. Many crystals have inclusions of earlier quartz, sericite, plagioclase, and, rarely, carbonate. In some rocks that have been subjected to deformation, orthoclase has crystallized in or adjacent to the fractures. In several specimens studied, orthoclase had formed in fractures that developed in pre-existing plagioclase. The orthoclase invaded along the fracture and began to replace the plagioclase adjacent to the fracture. In these instances, structural control for the solutional transfer of potassium is clearly demonstrated. In many instances, orthoclase is more abundant in areas where a considerable amount of late quartz is present. This relation is commonly noted within or adjacent to quartz veins, and further corroborates the idea of transfer of potassium and silica solutions via structural channelways.

Creasy (1959) noted the metastability of orthoclase in both clay and (or) clay-sericite alteration environments. In general, orthoclase appears to survive even where rather intense superimposed sericite alteration has occurred. In many rocks the orthoclase is unaltered or, at most, incipiently kaolinized or sericitized, whereas plagioclase has been almost totally destroyed by late sericite. Sericite development appears to postdate orthoclase. Had the reverse occurred, the sericite would have been at least partly replaced by orthoclase.

In many high-potassium alteration zones, the sulfides tend to occur in areas of orthoclase concentration, suggesting a close relation between late orthoclase formation and sulfide deposition. It is not known whether the orthoclase and sulfides are synchronous, but the relation does indicate that both materials used the same or similar channelways for solutional transfer.

Near Fortress Mountain, in eastern Snohomish County, an exception to the above was noted. A very intense stage of sericitization postdated orthoclase crystallization. This later alteration was so intense that it almost completely altered the orthoclase. In this zone, sulfide deposition reached a maximum. Adjacent rocks of similar composition not affected by this late sericitization, contain little sulfide. In this instance, sulfide deposition appears to have been related more closely to later hydrothermal activity than to earlier deuteric activity.

Secondary Biotite

Schwartz (1958) pointed out that, as a rule, biotite is unstable under hydrothermal conditions. This observation generally holds true throughout the Cascade alteration environments. Therefore, as the stability range of biotite is similar to that of orthoclase, biotite is considered another index mineral of the K-silicate type of alteration. Secondary biotite is also considered to be one of the most sensitive mineralogical indicators of potassium introduction. Pervasive, yet weak, biotitization, particularly affecting hornblende, commonly can be traced for thousands of feet outward from the central core of potassium alteration. In many areas, though, these effects, if previously existing, have been obliterated by the fringe propylitization.

Secondary biotite can be readily distinguished from primary igneous biotite by texture. In contrast with common euhedral to subhedral books of igneous biotite, secondary biotite occurs as fine-grained non-oriented crystals, either in a felty mat or as discrete grains superimposed over the earlier mineral fabric. In hand specimens, intensely biotitized rock commonly can be recognized by their purple-brown color. The felty biotite mats are commonly pseudomorphic after hornblende or earlier biotite. The first indication of secondary biotite formation normally is the incipient to moderate biotitization of hornblende, provided, of course, that hornblende is present. Increasing alteration intensity results in the destruction of earlier hornblende or biotite. In advanced stages of biotitization, the secondary biotite formation is ubiquitous throughout the rock. Most of the secondary biotite development is restricted to intrusive rocks. In the Fortress Mountain area (south of Miners Ridge), secondary biotite has developed in migmatitic gneiss lying adjacent to a small sulfide-bearing intrusive plug of quartz monzonite. There the gneiss probably was subject to contact potassium metasomatism, resulting in the crystallization of new biotite along S-planes.

Most of the secondary biotite is brown to reddish brown (Z) in thin section, as opposed to the common chocolate brown (Z) of primary biotite. Green (Z) biotite is thought to be a later, lower temperature variety, perhaps occurring transitionally between the reddish-brown biotite of the higher temperature alteration environment and the chlorites in the low-temperature stability field. In contrast with the stability range of orthoclase, secondary biotite under low-temperature conditions alters readily to chlorite. Of incidental interest is the unusual alteration of secondary biotite in the Buckindy Intrusive Complex, a heterogeneous granitoid mass on the north slope of Mount Buckindy, in the North Cascades. Here, relics of biotite are surrounded by sericite and chlorite, with magnetite occupying an interstitial position. This alteration, biotite → sericite + chlorite + magnetite, has been referred to by Misch (oral communication, 1965) as a "chemical reaction written in stone."

In most biotitized rocks, particularly those subjected to intense biotitization, K-feldspar is rarely present. The converse is true in K-feldspathized rocks. In the Middle Fork of the Snoqualmie area, a zone of heavy secondary biotite development surrounds an area where orthoclase has replaced most of the earlier silicate minerals of probable quartz diorite affinity. This peripheral biotite zone is thought to have resulted from the migration of iron and magnesium components from the replaced quartz diorite to the outer margins of the orthoclase zone. Here, in a potassium-silica-rich environment, the translocated ferrous iron and magnesium reacted with potassium and silica to form new biotite.

Paragenetically, in most areas, secondary biotite formation predates sulfide deposition, as evidenced by inclusions of secondary biotite in pyrite and chalcopyrite.

Chlorite Group

The chlorite group comprises an extensive series of isomorphous phyllosilicate minerals having a high degree atomic substitution. The complexity of chlorite mineralogy has been the cause of many workers' failure to distinguish specific varieties within the group. In the Cascades, petrographic studies have shown that different types of chlorite minerals form under fairly restricted conditions within the alteration environment. The prime controlling factor in this chlorite development appears to be temperature.

The common chlorites are basically products of low-temperature hydrothermal alteration. Their stability range is confined to the low-grade equivalent of the standard metamorphic zoning scheme. Stable magnesium-rich varieties have been reported in the lower medium grade, but these are rare and of no further concern here. In metamorphic rocks the boundary between chlorite and biotite constitutes an easily mappable isograde, approaching what might be considered a true isotherm because the influence of pressure does not appear to be significant. The boundary between the brown biotite and the chlorite is considered to roughly coincide with the line of demarcation between deuteric and hydrothermal alteration.

In the Cascade alteration environment, two principal chlorites are of interest; namely, clinochlore and pennine. These minerals cannot be distinguished in hand specimen. In thin section, however, clinochlore is characterized by X=Y= pale green and Z=colorless to weak tan. Pennine, on the other hand, has distinctly anomalous interference colors, the most characteristic being "Berlin, or ultra-blue."

The occurrence of pennine or clinochlore in the low-temperature alteration environment appears to be principally a function of temperature. Clinochlore generally develops directly after pre-existing mafics, and pennine develops after clinochlore. In rare instances, late clinochlore replaces pennine, as noted at the Miners Ridge copper deposit. There, earlier clinochlore was replaced by late pennine, which, in turn, was partially altered back to clinochlore, particularly in the central part of the mineralized zone. The recurrence of clinochlore could indicate that there was a slight increase in temperature after the low-temperature pennine stage.

The occurrence of chlorite obviously is dependent on the pre-alteration mineral constituents of the rock. In those areas where extensive K-feldspathization has obliterated much of the earlier texture and mineral assemblage, iron and magnesium are commonly driven off. Consequently, because of the absence of reactive components, chlorite is absent. When it does occur, it is generally clinochlore, unless superimposed low-temperature alteration in the pennine stability range has taken place, as is the case at Miners Ridge.

Chlorite types are commonly related to the intensity and type of sulfide deposition. At Miners Ridge, clinochlore development is strongest in the area of highest copper sulfide deposition. Several miles to the south, at Fortress Mountain, pennine is the principal chlorite in the copper-molybdenite zone. In the Middle Fork area, clinochlore predominates in the copper zone whereas pennine characterizes the outer propylite-pyrite zone. At the Miners Queen prospect (in southern Skamania County), pennine occurs after secondary biotite in the chalcopyrite areas.

Sericite

Sericite is a general term referring to fine-grained muscovite. Its fine-grained nature commonly causes difficulty in accurately distinguishing sericite from other minerals such as paragonite. In most instances, though, sericite is thought to be compositionally similar to muscovite.

The occurrence of sericite itself is not considered to be a good index of the alteration type. Rather, it is the intensity of sericitization that appears to be of significance. Fine-grained pervasive sericitization has normally occurred to some degree in all alteration environments. As the intensity of alteration increases, the sericite becomes more coarse grained and commonly forms rosettes. This rosette development is of particular importance. Generally, it is not found in propylitized rocks. In quartz-sericite altered rocks, the rosette development varies from that incorporating very fine-grained sericite to that with coarse-grained muscovite. Coincident with the muscovite rosettes are the most intense degrees of alteration and sulfide (quartz-sericite zone only) deposition.

Sericite most commonly forms after plagioclase. Incipient sericitization generally is controlled by the plagioclase cleavage. As the alteration process continues, the sericite development becomes more ubiquitous in the plagioclase crystal, until eventually the plagioclase is pseudomorphed by sericite. This alteration normally is accompanied by decalcification of plagioclase. Sericite rarely forms after biotite. As previously mentioned, K-feldspar commonly resists sericitization attack.

In areas of less intense alteration, sericitization and chloritization generally are restricted to areas adjacent to small veins, commonly filled with quartz, or to small fractures. These relations indicate that the alteration is principally structure controlled.

If it is assumed that most of the sericite formed after plagioclase is actually muscovitic in composition, then intense sericitization must necessitate the introduction of potassium. The development of sericite rather than orthoclase appears to be primarily a function of the P/T stability fields of these minerals. Some of the white mica that resembles sericite may actually be paragonite derived from albite.

Miscellaneous Alteration Minerals

The foregoing discussions have dealt with the most important of the alteration minerals associated with Cascade sulfide deposits. Many other minerals, some of them diagnostic within certain alteration types, should be mentioned briefly.

Epidote is an index mineral of the propylite zone. Most commonly it develops after plagioclase, utilizing the anorthite molecule. The degree of epidotization is sometimes a direct function of the degree of plagioclase decalcification. Commonly, even though the plagioclase has been extensively decalcified, epidote, or any other anorthite substitute mineral, is not present in sufficient amounts to satisfactorily explain the anorthite loss. In these instances, it is believed that the calcium has been driven off during the alteration process or has combined with carbonate to form calcite. For example, adjacent to an area of intense plagioclase decalcification on the Middle Fork of the Snoqualmie River, an epidote-rich halo has developed. This relation suggests that the migrating calcium was concentrated in an area peripheral to the decalcification.

Where the epidote variety is pistacite, it may have utilized ferric iron released during the biotitization of hornblende or the chloritization of biotite. The occurrence of sphene in the alteration halo in intrusive rocks could be related to alteration of igneous hornblende.

As quartz occurs in all environments, it cannot be considered an index mineral. In general, substantial quartz development indicates silica introduction, but in some cases, particularly where there has been extensive replacement of plagioclase by orthoclase, substantial amounts of silica probably have been released from the plagioclase. In rare instances, silica has been leached from altered rocks through which hydrothermal solutions passed. This leached silica was probably redeposited as a siliceous halo around the altered zone.

Quartz commonly replaces plagioclase; less commonly, K-feldspar; and rarely, muscovite. In most alteration zones, several periods of silicification have occurred. The earlier periods are generally characterized by replacement quartz in the rock fabric. The later periods of quartz activity are most commonly characterized by vein quartz along late fractures.

Other minerals frequently noted in the altered rocks are actinolite, siderite, calcite, and tourmaline. Actinolite does not appear to be of particular significance. It forms most commonly after hornblende in the outer fringe of altered rocks. Carbonate, both calcite and siderite, is relatively common in intensely altered rocks, particularly in those of the quartz-sericite type. Calcite may form in a high carbon dioxide environment by utilizing calcium released from decalcified plagioclase. Tourmaline does not serve as a diagnostic index mineral in Cascade ore deposits. In some places, such as at Miners Ridge, both schorlite and elbaite form in the main sulfide zone. In the Quartz Creek breccia pipes (see page 79), probable lithium-bearing tourmaline occurs with anthophyllite as gangue in massive replacement lenses of sulfide. At other properties, tourmaline is either absent or occurs along the fringes of the sulfide zones.

CHEMISTRY OF THE ALTERATION SYSTEMS

The chemical compositions of the deuterically and hydrothermally altered rocks have been calculated from modal analyses. The compositions of the various mineral components used in these calculations were taken from Deer and others (1962). The calculated major oxide and cation percentages were compared with computer results of data that had been programmed by Dr. A. J. Sinclair of the University of British Columbia, using the same base modal data but slightly different mineral composition standards. The calculated and the computer results varied little. It is hoped that, eventually, comparable suites of samples can be spectrographically analyzed. The oxide percentages may vary, but the gross chemical patterns will remain similar.

The relation between deuteric and hydrothermal alteration has already been discussed. I feel that the K-silicate alteration can be roughly equated to the pegmatitic or deuteric phase of an intrusive cycle. The residual system from fractional crystallization of a magma will, in general, be a siliceous liquid, rich in alkalies and alumina. This liquid has been called "petrogeny's residua system" (Bowen, 1937), indicating the ternary system $NaAlSiO_4 - KAlSiO_4 - SiO_2$ that was worked out by Schairer and Bowen (1935). Mason (1958) stated that such a residual liquid would probably be highly fluid on account of the high concentration of volatiles. This process then could result in the formation of pegmatites or of deuterically or hydrothermally altered rocks, as the case may be.

Many geologists feel that hydrothermal activity postdates the quartz-alkali feldspar-mica stage. Shand (1944) stated that the post-magmatic (a poor term; a better one is late-magmatic) processes are assigned to the earlier deuteric or high-temperature hydrothermal stage or to the later low-temperature hydrothermal stage. For reasons previously discussed (on page 47), the term "deuteric" will be restricted to the earlier late-magmatic processes and "hydrothermal" to the last stage of the magmatic process.

TABLE 3.—Weight percent of the major oxides (calculated from modes) in the main-phase Snoqualmie quartz diorite and its various altered equivalents—Middle Fork Snoqualmie area, King County. Sulfide content is purposely omitted from these data.

	Snoqualmie quartz diorite main-phase (eleven modes) (Erikson, 1965)	Orthoclase alteration (eight modes)	Biotite alteration (five modes)	Quartz-sericite alteration (six modes)	Propylitic alteration (eight modes)
SiO_2	65.8	67.2	57.8	73.1	66.1
Al_2O_3	16.5	19.5	19.7	12.9	15.9
Fe_2O_3	0.4	tr	1.1	0.3	0.5
FeO	4.7	tr	4.0	0.9	5.2
MgO	1.7	tr	2.8	0.7	4.1
CaO	4.7	0.2	2.8	----	2.9
Na_2O	2.5	0.2	2.7	0.2	2.4
K_2O	2.9	11.6	7.1	4.0	1.5
H_2O	0.5	1.2	1.3	3.1	1.5
TiO_2	0.1	----	----	----	----
Totals	99.8	99.9	99.3	95.2	100.1

Table 3 shows the calculated major oxide percentages of the various alteration types within the Snoqualmie batholith as compared with the main-phase unaltered Snoqualmie quartz diorite. The altered samples were collected in the Middle Fork of the Snoqualmie River area. The principal sulfides associated with the altered rocks are shown in Table 4.

TABLE 4.—Variations in sulfide content within the principal alteration types in the Middle Fork of the Snoqualmie River area. Data based on megascopic estimates.

Alteration type	Total sulfides (percent)	Principal sulfides
Orthoclase	6	Chalcopyrite, pyrrhotite
Biotite	5	Chalcopyrite, pyrite
Quartz-sericite	6	Chalcopyrite, pyrrhotite, pyrite
Propylitic	<2	Pyrite

The data in Table 1 indicate wide variations in the compositions of the various altered rocks and their probable parent material. It is assumed that the original rock subjected to alteration was main-phase Snoqualmie quartz diorite. In the orthoclase alteration, the substantial decreases in sodium and calcium reflect the wholesale replacement of plagioclase by orthoclase. Sodium and calcium probably migrated to the periphery of the K-silicate zone. The practically nil iron and magnesium content is indicative of the removal of all ferromagnesian minerals from the orthoclase environment. The significant increase in potassium is obviously due to orthoclase development and, in most instances, subordinate superimposed sericitization of plagioclase relics. The hydroxyl content increases as a result of this hydrothermal action. The increased silica content could be a function of both (1) the replacement of plagioclase by orthoclase and (2) the sericitization of plagioclase. These reactions can be expressed by the following general equations (assuming original plagioclase to be andesine) modified from Hemley and Jones (1964).

$$\text{(1)}\quad \underset{\text{Andesine}}{Na_2CaAl_4Si_8O_{24}} + K^+ = \underset{\text{Orthoclase}}{KAlSi_3O_8} + Ca^{++} + Na^+ + SiO_2$$

$$\text{(2)}\quad \underset{\text{Andesine}}{Na_2CaAl_4Si_8O_{24}} + H^+ + K^+ = \underset{\text{Sericite}}{KAl_3Si_3O_{10}(OH)_2} + Ca^{++} + Na^+ + SiO_2$$

These equations are obviously oversimplified. For example, under normal conditions, the plagioclase remaining during the orthoclase stage would probably be albitized prior to sericitization.

The biotite alteration type is characterized chemically by gains in iron, magnesium, and potassium and by corresponding losses in calcium and silica. These dominant compositional changes reflect the biotitization (and subordinate K-feldpathization) process accompanied by decalcification or sericitization of remaining plagioclase.

TABLE 5.—Weight percent of the major oxides (calculated from modes) in the main-phase Cloudy Pass Quartz Diorite and its various altered equivalents. Sulfide content is purposely omitted from these data.

	Cloudy Pass Quartz Diorite main-phase (unaltered) (33 modes)	K-silicate alteration (16 modes)	Quartz-sericite alteration (26 modes)
SiO_2	61.0	68.9	75.8
Al_2O_3	19.6	17.5	11.7
Fe_2O_3	0.3	tr	tr
FeO	5.9	tr	tr
MgO	1.6	0.2	tr
CaO	5.7	0.9	3.0
Na_2O	2.8	2.1	0.1
K_2O	1.8	9.1	6.3
H_2O	0.4	0.4	0.8
TiO_2	0.1	---	---
CO_2	---	---	2.3
Totals	99.2	99.1	100.0

The quartz-sericite alteration invironment is, as expected, rich in silica and potassium and poor in ferromagnesian minerals. It is characterized by a relatively simple assemblage of silicate minerals. The chemical composition of this alteration type broadly reflects the overall simplicity.

Propylitized rocks generally retain an overall composition similar to that of the parent rock. The major elements are redistributed to form new minerals. In the propylitized Snoqualmie rocks, an increase in magnesium (reflecting the chlorite development) and a decrease in calcium and potassium are the principal element changes. The plagioclase is always albitized, much of the calcium being utilized in epidote development or, if carbon dioxide is present, in calcite.

Table 5 shows the calculated chemical composition for the main-phase Cloudy Pass Quartz Diorite and its various altered equivalents. No samples from the propylitized zone were studied. The overall chemical changes in the Cloudy Pass rocks show gains and losses similar to those in the Snoqualmie rocks.

The overall gains and losses for the "average" alteration types in the Cascade environment are shown in Table 6. These data are presented to illustrate the gross chemical relations in the various alteration systems. They are not intended to be used as a guideline for specific areas. Included in this tabulation are chemical compositions of rocks (unaltered and altered) collected from the Perry Creek intrusion, the Cloudy Pass batholith, the Snoqualmie batholith, and the Silver Star stock.

TABLE 6. — Weight percent gain or loss of elements in the various alteration types present in the Cascade environment. Data represent absolute changes from the norm established in the study area.

Element	K-silicate (orthoclase and biotite)	Quartz-sericite	Propylitic
Si	+1.2	+10.1	+0.3
Al	+0.8	-5.8	-2.2
Fe^{+++}	no change	-0.2	-0.2
Fe^{++}	-4.0	-4.8	-0.1
Mg	-0.7	-1.6	+2.4
Ca	-3.9	-3.7	-2.3
Na	-1.2	-2.5	-0.1
K	+6.0	+4.4	-0.8
OH^-	+0.5	+1.4	+1.1

In general, the present status of knowledge of wall rock alteration as related to Cascade sulfide deposits is in what might be called the "reconnaissance" stage. There have been established certain fundamental relations that equate intrusive chemical processes to the various alteration systems. These alteration systems, in turn, have been related to various periods and types of sulfide deposition. Such information has proven valuable in the interpretation of environmental control factors.

To anticipate exploration needs, however, further detailed study in this field is appropriate. For example, it has been pointed out that much of the range, away from the zones of exposed plutons, is thought to be underlain by large masses of intrusive rock. This possibility is particularly evident in the South Cascades, where, in spite of the absence of exposed granitic rocks, extensive areas of lower-middle Tertiary volcanic rocks are hornfelsed and hydrothermally altered. Detailed studies of the alteration halos in these volcanics might reveal clues to the chemical nature of the suspected subjacent intrusive mass. This information, coupled with geochemical analyses for base metals and with trace element distribution studies, could delineate potential exploration targets.

SUPERGENE ALTERATION

Supergene alteration and attendant leaching of sulfides have long been recognized as a critical guide in the search for ore, particularly in areas such as the southwestern United States. Locke's (1926) classical work on leached outcrops is still considered an excellent reference on this subject.

The significance of leached outcrops in an area such as the Cascades has never been fully recognized. It has been generally accepted by most earlier Cascade workers that leaching and supergene alteration, although occurring over most lode sulfide deposits, were not of particular importance. The rugged character of the mountains and the relatively recent glaciation and rapid erosion allow little chance for protracted periods of chemical alteration on the surface. Nevertheless, as the search for ore continued, particularly for low-grade disseminated copper deposits, the importance of supergene alteration became more apparent. In contrast with zones in the Southwest, where economically important concentrations of enriched copper ore commonly occur at the base of the supergene layer, zones of secondary copper enrichment that exist over Cascade deposits. are very small and rarely of any economic importance. The principal significance of supergene alteration in the Cascades is that it tends to conceal the underlying primary mineralized rock. The supergene "skin" usually varies in thickness from less than 1 inch to several feet, but in some isolated instances, particularly over intensely brecciated rocks, the thickness may exceed 20 feet. In general, however, the supergene zone can be easily penetrated by drilling with a small, lightweight rock drill and by blasting.

The surface of these supergene zones can be recognized easily by the bleached, punky character of the rock. Limonite minerals generally are present but in highly variable amounts and types. Downward from the surface, in a typical cross-section profile, the following relations are common over disseminated copper sulfide zones:

Surface to 3 ft	Supergene quartz-sericite Moderate limonitization Sulfides absent Traces of oxide copper
3 to 4 ft	Supergene quartz-sericite Decreasing limonitization Supergene sulfides (pyrite and marcasite)
4 ft	Supergene quartz-sericite, decreasing Traces of enriched copper sulfides
Below 4 ft	Biotite-orthoclase alteration Hypogene pyrite-chalcopyrite in varying ratios

Near-surface fractures allow supergene alteration to penetrate well into the primary silicate-hypogene sulfide zone. Where this penetration occurs, the supergene activity is guided by and restricted to the fracture.

As a general observation: supergene quartz-sericite tends to form over highly reactive sulfide-bearing rocks, particularly those subjected to the K-silicate or primary quartz-sericite alteration. The acidic nature of the parent rock, coupled with sulfide leaching,appears to trigger fairly rapid supergene processes.

Limonite mineralogy is of special note within these leached outcrops. Those minerals that commonly occur in oxidized cappings over sulfide deposits include goethite, hematite, and jarosite. Locke (1926) indicates that limonite mineralogy varies with the original sulfide mineralogy. In general, the brick-red to yellowish limonites, characterized by jarosite and goethite, tend to form during the oxidation of pyrite, and the ocherous to orange limonites, characterized by hematite and jarosite, tend to form over oxidized chalcopyrite. There has been considerable refinement of these earlier data, but the basic relations still hold true, even in such areas as the Cascades. Economic geologists working in the range will readily note the existence of numerous gaudy brick-red pyrite gossans, commonly adjacent to intrusive contacts. Rarely do these zones contain much base metal material. The more subtle reddish-brown to orange-brown limonite gossans commonly result from the oxidation of chalcopyrite and (or) chalcopyrite-pyrite. Care must be taken in the field to distinguish the natural limonites from those caused by artificial means. For example, in areas where forest fires have occurred, hematite commonly develops in the surface rocks as a result of heat.

The development of supergene sulfides at the base of the leach zone is worthy of special comment. In certain areas, pyrite and marcasite form as massive blebs (in amounts up to 15 percent by volume) directly over hypogene sulfide zones (total sulfide 3 to 6 percent by volume). The occurrence of these supergene sulfides appears to be indicative of a reducing rather than an oxidizing environment. This theory is further corroborated by a change in the limonite mineralogy. The sulfate jarosite occurs in the zone of oxidation, but goethite is present in the zone of reduction. These phenomena apparently are related in part to the variations in soil chemistry on humid-forest-covered slopes over sulfide-bearing rocks. Little detailed information on these processes is available.

PHYSICAL AND CHEMICAL CONTROLS FOR SULFIDE DEPOSITION

GENERAL CONSIDERATIONS

The preceding sections of this paper have dealt with the structural and chemical environments in the Cascade Range associated with sulfide deposits. These variables will now be directly related in time and space to the problems of economic geology. Before commencing, however, it is important to consider these variables and their spheres of influence.

Jerome and Cook (1967) noted the remarkable coincidence of structure, intrusive igneous centers, and the timing of igneous activity with the formation of ore bodies in the Western Cordillera of the United States. They pointed out the striking regional alignments of intrusive centers, mining districts, and individual ore deposits. In particular, they considered the combination of deeply penetrating zones of weakness and deep-seated igneous and thermal activity to be a critical control necessary to produce major concentrations of metalliferous material, if indeed such material were present.

Bichan (1957) outlines a series of factors that he feels are imperative to the exploration geologist in his search for hypogene ore. Briefly, these are:

Differential rock competence
Degree and extent of fracturing
Propinquity of access channels
Tensional dilation
Thermal conditioning
Redistribution of valuable mineral content
Time relation with regional forces

All these criteria are geologically important, but they are, in part, meaningless unless placed in their proper perspective. At this point perhaps it is advisable to consider the nature of an ore body. By definition, it represents a natural anomaly; i.e., a concentration of valuable material that under normal conditions is widely disseminated in the earth's crust. Therefore, because of the anomalous nature of a sulfide deposit, it would seem reasonable to expect an overall anomalous environment as compared with the regional norm. To illustrate a case in point, consider the intrusive chemistry of the allochthonous Great Basin plutons as compared with that of the autochthonous plutons of the West Cordilleran System. In the Great Basin the intrusions are typically potassium-rich (quartz monzonite-granodiorite) in composition. The West Cordilleran plutons, on the other hand, are mostly quartz dioritic. In the Great Basin, ore deposits commonly are associated with quartz monzonite intrusions; however, many other quartz monzonites in the same region are relatively barren of base metals. Therefore, in the

Great Basin Province a potassium-rich pluton is not necessarily an anomaly. Other environmental criteria, such as structure and intrusive differentiation, must have been major controlling factors for the concentration of ore. In the West Cordilleran System, however, the occurrence of potassium-rich intrusive rocks is anomalous and constitutes one of the critical guides in the search for ore deposits in that area. In other words, a geologic anomaly is a departure from the regional background, which, in turn, varies considerably from one geological province to another.

Other critical variables that could significantly affect the environment of sulfide deposition are noted below.

Rock competence. — Bichan (1957) notes that fracture systems within a heterogeneous and anisotropic host mass are susceptible to a greater degree of tensional dilation than are those in a homogeneous rock sequence. In many instances, the thoroughness of wall rock alteration is partly determined by the intensity of wall rock fracturing.

Variations in wall rock chemistry. — The availability of reactive wall rock constituents is an important factor in the resultant alteration mineral assemblage. For example, potassium metasomatism in mafic-rich rocks, particularly those rich in hornblende, would be likely to produce secondary biotite. Conversely, potassium introduction into quartzo-feldspathic rocks normally results in the formation if K-feldspar.

Pressure-temperature variables. — Rock alteration, being essentially a type of metamorphism, is strongly influenced by P/T variations. Alteration itself is a physical response to changes in environment. An alteration reaction tends toward the formation of a new stable mineral assemblage. In general, however, conditions of stability are rarely reached. The degree of stability of a given mineral assemblage is primarily determined by P/T ratios, P including partial pressure of such volatiles as water and carbon dioxide. Continuous changes in these physical conditions in an open natural system could certainly affect the end products.

The availability of introduced material. — This factor is obvious. More intense potassium alteration, for example, depends upon the amount of potassium introduced into the system. This total availability could depend on primary magmatitic differentiation processes.

Observation levels. — Geologists have long recognized spatial variations in a given system. Alteration phases commonly vary laterally and vertically. It is important to recognize the physical level of observation and to place it accurately in the three-dimensional picture.

The reader can readily comprehend how meaningless much of the observable data could be without proper orientation in the regional picture. As base metal exploration continues, the need becomes more pressing for fundamental understanding of the background environments, against which anomalies can be more readily recognized.

In the Cascade Range of Washington the background geologic environments are reasonably well established. The petrology and distribution of the major rock units have been outlined. In the crystalline core of the North Cascades, the petrogenetic relations of the complex metamorphic-plutonic rocks have been delineated. The regional structural patterns are well known. The various periods, types, and possible mechanisms of the intrusive cycles are documented. A point has been reached in regional understanding where some anomalous features can be recognized. Those of principal significance are wall rock chemistry, alteration phases, and crosscutting structural patterns.

The total sulfide content in rock commonly is directly related to the degree and type of alteration, which, in turn, is related to the intensity and type of fracturing. As previously discussed, orthoclase-biotite and quartz-sericite alteration predominate in the areas of highest sulfide concentrations. Quantitatively, this relation is shown in Table 7 for rocks in the Snoqualmie and Cloudy Pass batholiths. These data are represented graphically in Figure 18.

An analysis of Cascade structural data in areas of base metal deposition tends to clearly demonstrate the tendency of sulfides to concentrate in areas where anomalous fracture patterns exist. The transverse structural belts, as previously outlined, have significantly influenced the distribution of base metal occurrences. This can be readily illustrated by the strike diagrams in Figure 19 for shearing in the southern part of the Cloudy Pass batholith and the adjacent migmatitic gneisses. The distribution of strikes of the non-mineralized shears is highly variable. The mineralized shears, however, show a trend

TABLE 7.—Variation in sulfide and copper content in the principal alteration types of the Cloudy Pass and Snoqualmie batholiths. Data are quantitative estimates.

Type	Snoqualmie batholith	Cloudy Pass batholith
Main phase	Nil sulfides	Nil sulfides
Propylitic phase	2 percent sulfides 0.1 percent Cu	No data available
Quartz-sericite phase	6 percent sulfides 0.5 percent Cu	5 percent sulfides 0.7 percent Cu
K-silicate phase	6 percent sulfides 1.0 percent Cu	6 percent sulfides 1.0 percent Cu

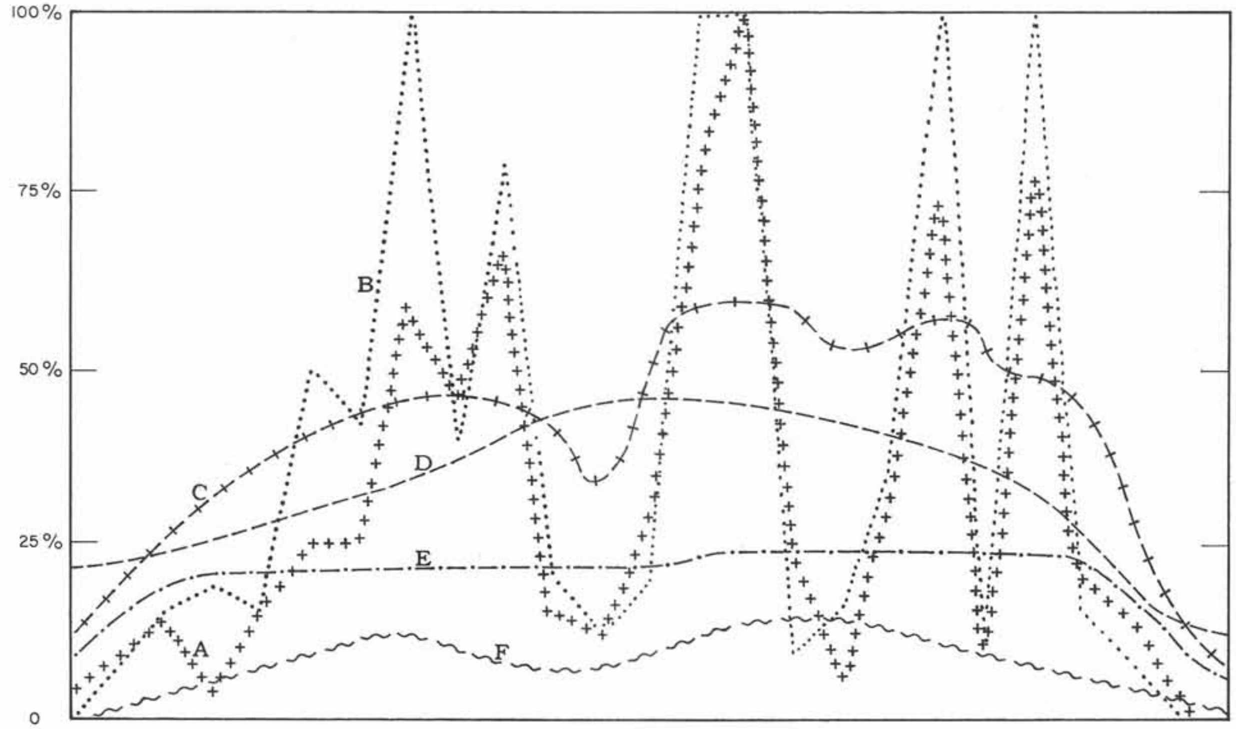

FIGURE 18.—Composite graphic representation of a mineralogical alteration profile as associated with a "typical" Cascade porphyry copper deposit. Hydrothermal alteration sequence (chlorite and sericite) superimposed over deuteric K-silicate sequence.

A. Sericitization - percent of secondary sericite to total feldspar in rock.

B. Chloritization - percent of chlorite to total mafics present in rock.

C. Total K-feldspar in rock.

D. Total quartz in rock.

E. Total secondary biotite in rock.

F. Total sulfide in rock.

to strike parallel to the transverse structural trends. In most instances, sulfides occur in the east-west fractures at points of intersection with the complimentary north-south fracture system. The resultant tensional dilation from this intersection is restricted to the east-west planes. Similar patterns have been noted in other mining districts. The significance of major structural couples in the emplacement of acidic intrusive rocks and of associated sulfide mineralization has previously been discussed.

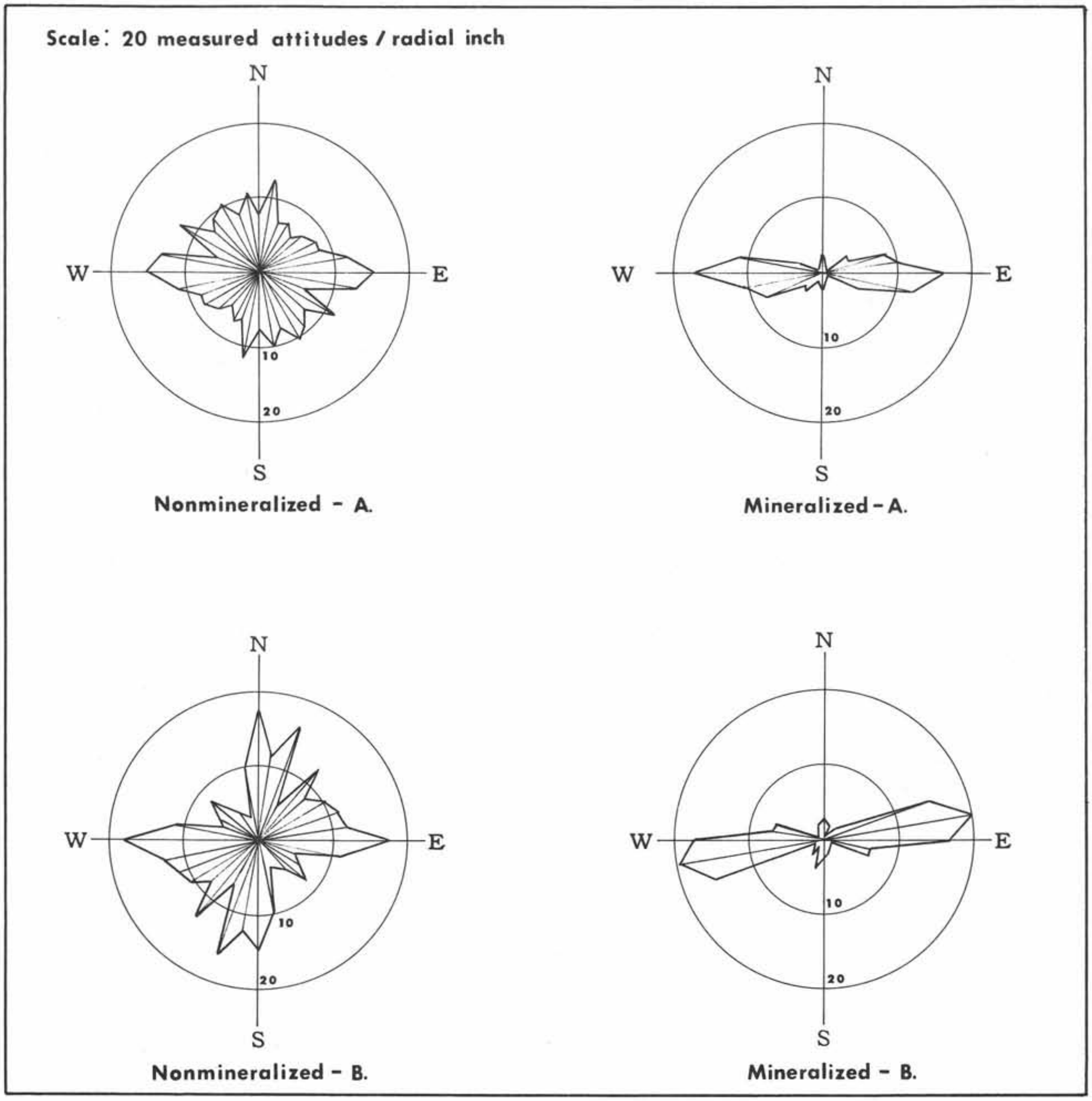

FIGURE 19.—Strike diagram showing the directional frequency of sulfide-bearing versus barren shears in intrusive and metamorphic rocks cut by transverse structures in the Miners Ridge area. T. 31 N., Rs. 15, 16 E.

A. Directional frequency of shearing in pre-Tertiary metamorphic complex.

B. Directional frequency of shearing in Cloudy Pass pluton.

Stringham (1960) compares the various characteristics of barren versus productive intrusions in the Western Cordillera. Table 8 outlines his principal criteria.

TABLE 8.—Major characteristics of barren and productive intrusive porphyries in the Western Cordillera. Criteria listed in order of importance. After Stringham (1960).

Barren	Productive
1. Forceful mode of emplacement	1. Passive mode of emplacement
2. Strong flowage features	2. Weak flowage features
3. Prominent cooling features	3. Weak cooling features
4. Varied composition	4. Uniform composition
5. Gradational borders	5. Sharp borders
6. Little contact action	6. Much contact action
7. Usually not altered	7. More susceptible to be altered

This method of "pigeonholing" intrusive characteristics as a guide to ore is not necessarily advocated. However, it might be appropriate to apply Stringham's criteria to the Cascade intrusions. Cascade plutons are both forceful and passive in their emplacement. Some of the significant sulfide deposits are situated within areas of intrusive brecciation. In other places, intrusive tectonics have strongly influenced the structural controls for later sulfide deposition. Rarely do the Cascade plutons exhibit significant flow features. Many, however, exhibit textural and compositional variations related to cooling phenomena. Most of the intrusions are composite in nature, having several intrusive phases. The rare plutons of relatively uniform composition appear to be mostly barren of sulfides. Intrusive contacts are generally sharp, rarely gradational. Chemical interaction of the intrusive mass with the country rock is highly variable and is principally dependent on the nature of the wall rock. Alteration factors are so complex and are subject to so many variables that it is impossible to lump this criterion.

DESCRIPTIVE AREA STUDIES

The following section contains areal descriptions of a few selected mining properties and (or) districts and is intended to illustrate the complex relations between sulfide deposition and Tertiary intrusive activity, tectonics, and alteration. Locations of these areas are shown on Figure 20. It is not the purpose of this section to evaluate economically any given area as to its base metal potential. All reference to possible tonnages and expected or known grades is purposely omitted. Many significant mining properties or districts in the range are not discussed. This omission is not intended to reflect unfavorably upon these areas.

In selecting the various areas to be discussed, an attempt has been made to include those that illustrate a wide variety of physical conditions. Four fundamental environmental criteria have been outlined in preceding sections of this report, all of which appear to have significantly influenced the mode and character of sulfide occurrences. In general order of importance, these criteria are:

1. Adjacent or subjacent post-regional metamorphism high-level intrusive activity. Middle-upper Tertiary intrusive episodes (ranging in age from 17 m.y. to 30 m.y.) appear to represent the most important phase of this period of granitic evolution, as related to ore deposition.
2. Transverse structural belts, occurring generally as northeast-southwest- to east-west-trending en echelon fracture systems, which obliquely cut the northwest regional trend in the range.
3. Potassium-silica wall rock alteration, the source of which is thought to be late magmatic residual volatiles.
4. Structural intersections.

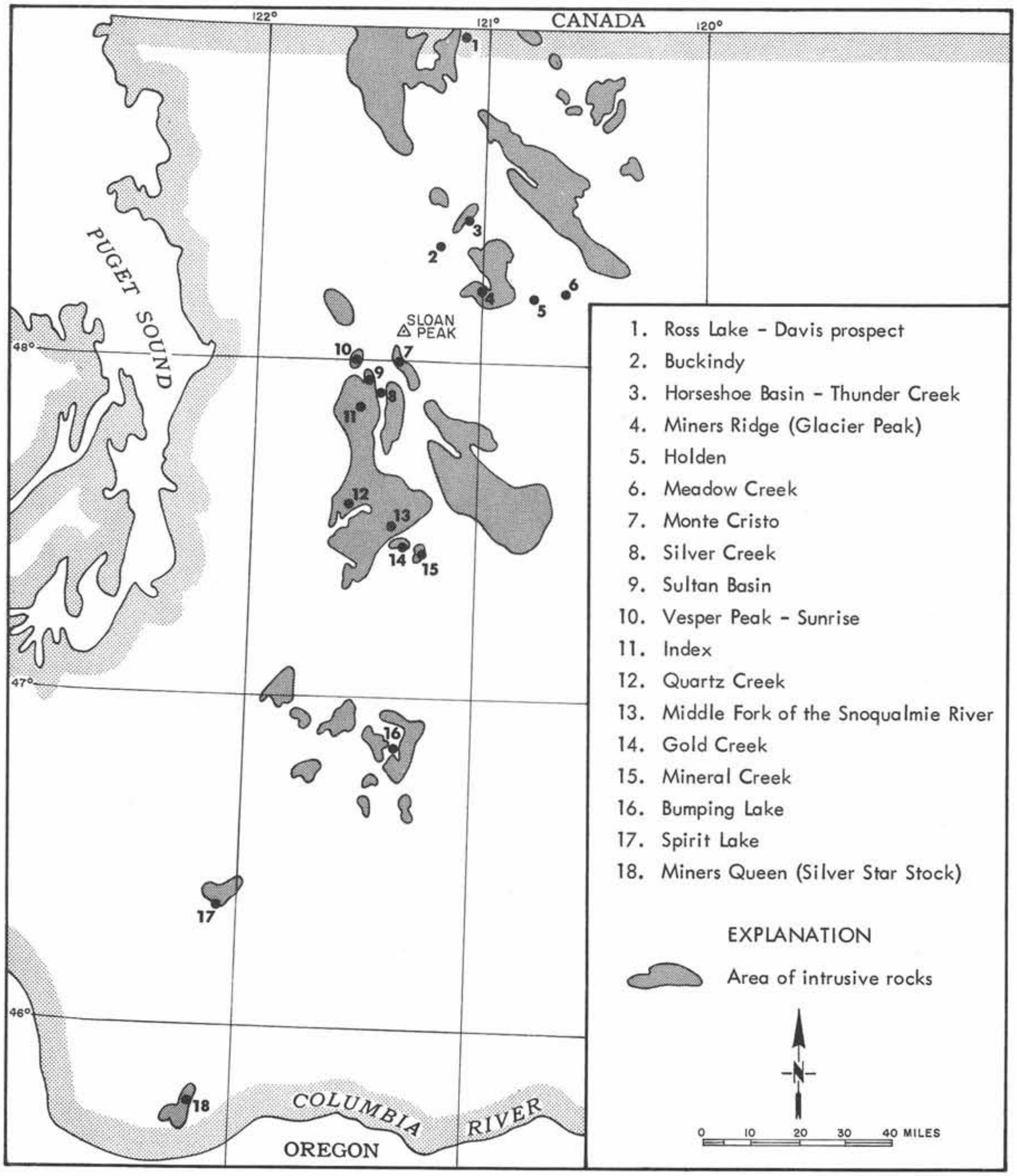

FIGURE 20. — Index map of the prospects and areas discussed in this paper.

In the following section the reader will note that some of the areas discussed exhibit all the above characteristics whereas others do not. In the latter areas, sulfide deposition commonly is pervasive but lacks concentration. Summary of areas discussed, general environments, and sulfide concentrations are presented in Table 9.

Before discussing the selected areas of interest, it might be well to summarize the basic types of base metal occurrences. The Cascade Range is, from the standpoint of economic mineral potential, a copper province. Various other metals, such as lead, zinc, gold, silver, and nickel, occur in lesser quantities and, in many occurrences, are associated with the

TABLE 9. — Summary of geologic environments and significant structure-alteration relations affecting, in part, the type and distribution of sulfides at properties discussed in this paper

Area and location	Country rock	Intrusion type and age	Transverse structures	Structural intersections	Alteration	Sulfide occurrences
Northern Ross Lake, Whatcom County	Eocene volcanics	Quartz-diorite. Subjacent. ± 30 m.y.	Northeast bedding in volcanics. Some east-west fracturing	None known	Orthoclase-biotite	Pods, disseminations and veinlets in altered tuff horizon
Buckindy structural belt, Skagit County	Pre-Tertiary migmatitic gneiss	Pre-Tertiary syn-metamorphic quartz diorite pluton	East-west sheeting and foliation in metamorphic rocks	None known	Propylitic, weak quartz-sericite	Scattered veinlets in gneiss and adjacent intrusion
East Glacier Peak structure, Snohomish and Chelan Counties	Pre-Tertiary metamorphic complex	Composite; mainly quartz diorite, late granite. ± 22 m.y.	East-west en echelon sheeting	Northwest folds in metamorphic rocks, east-west sheeting	Orthoclase, quartz-sericite	Disseminations in quartz diorite and gneiss; local fracture fillings
Silver Creek-Sultan Basin, Snohomish County	Mostly Mesozoic-Tertiary sediments and volcanics	Quartz diorite, local granite. ± 18 m.y.	East-west en echelon sheeting	Rare northwest faults; east-west shears	Propylitic, weak orthoclase-biotite	Pervasive fracture filling; rare localized dissemination
Index district, Snohomish County	Upper Paleozoic-Tertiary sediments and subordinate volcanics	Quartz diorite. ± 18 m.y.	East-west en echelon sheeting	Northwest faults; east-west shears	Weak orthoclase-biotite	Lode and fracture fillings
Quartz Creek district, King County	Upper Mesozoic sediments Tertiary volcanics	Composite; diorite, quartz diorite, quartz monzonite. ± 18 m.y.	East-west shearing	North-trending faults?	Biotite; superimposed chlorite-sericite	Open space fillings in breccia pipes; fracture fillings
Middle Fork Snoqualmie River area, King County	Tertiary volcanics	Composite; quartz diorite, local quartz monzonite. ± 18 m.y.	Northeast-trending shearing	North-northwest-trending faults	Biotite-orthoclase, quartz-sericite, propylitic halo	Disseminations, stockworks, breccia pipes, replacement breccia, fracture fillings
Western Kittitas County	Tertiary volcanics	Quartz diorite. ± 18 m.y.	Northeast sheeting, not pronounced	Northwest folds and faults	Propylitic, grading downward to biotite	Mostly fracture fillings, local breccias, weak dissemination
Silver Star stock, Skamania County	Tertiary volcanics	Granodiorite. Age unknown, possibly <15 m.y.	More or less east-west shears	Questionable northwest shearing	Biotite-orthoclase, quartz-sericite	Fracture fillings, localized breccias

predominant copper mineralization. Although various types of sulfide deposits occur in the Cascade Range, most are thought to be genetically related to intrusive activity. These deposits are divided into five major classes.

Disseminated deposits. — Disseminated copper deposits are associated almost exclusively with potassium-rich intrusive rocks. These deposits are similar to the large porphyry copper deposits found in the southwestern United States. The "porphry coppers" in the Cascades differ from those in the Southwest in one important aspect. Only minor oxidation and leaching have taken place in the Cascade deposits, and thus no economically important zone of secondary enrichment is present. Mining economics in the Cascades must depend upon the metal content in the hypogene sulfides.

Several of the larger disseminated copper deposits are surrounded by sporadic occurrences of lead and zinc, thus creating a crude pattern of lateral base metal zonation. Vertical changes in sulfide mineralogy have also been noted. Of particular significance is pyrrhotite in lieu of pyrite in the copper environment at depth.

Breccia pipes and shatter pipes. — Mineralized breccia pipes are common in the Cascade Range. Most are situated adjacent to contacts of intrusive bodies. Commonly, the matrix of these breccias consists predominantly of quartz and sulfides. The pipes appear to be associated mostly with late-stage magmatic activity. In at least one instance, correlation of fragment lithologies in the pipe with overlying country rock suggests that collapse occurred. In general, the pipes are characterized by (1) more or less crude cylindrical or oblate spheroid shapes, (2) vertical or steep contacts, (3) a vertical axis considerably greater in length than the maximum horizontal dimension, and (4) variable lithologies of incorporated fragments. Commonly, the fragments are subrounded or streamlined. Structural control for those pipes occurring at the intersection of northwest and northeast structures is obvious. For many other occurrences, however, no apparent relationship between the pipe and other structures is recognized.

Numerous brecciated areas, not classified as breccia pipes, are termed shatter pipes. These pipelike structures do not exhibit the intensity of fracturing found in the breccia pipes. No rotation, rounding, or lithologic variation of the fragments has occurred. Rather, these shatter pipes are zones of rock fracturing and breaking without obvious movement. Various stages of alteration and replacement are found in these shatter zones. A probable sequence of events leading to the formation of these pipes is as follows:

1. Incipient to intense fracturing of the intrusive rock.
2. Metasomatic introduction, predominantly of potassium and silica, utilizing pre-existing structures as avenues for solutional transfer.
3. Formation of biotite and (or) K-feldspar in the breccia matrix.
4. Partial replacement of the country rock fragments by matrix material, culminating sometimes in the destruction of many earlier magmatic textures in the fragments.

The end product resembles a replacement breccia with hazy relics of the original intrusive rock fragments. Sulfide mineralization generally is restricted to the matrix material in these shatter pipes. Metallization is thought to be contemporaneous with or to slightly postdate the introduction of matrix material.

Stockworks. — Stockwork deposits locally occur along or near intrusive contacts. This type of deposit is characterized by extensive fracturing of the country rock and little or no preferred structural orientation in the fracture patterns. Quartz and sulfides occur along the fractures. Rock alteration is pervasive but generally not intense, and in many areas has not advanced beyond the propylitic stage. Many of the more promising occurrences of molybdenite in the range are found in stockwork environments.

Lodes. — Lode deposits are the most common type of mineral occurrence in the Cascade Range. Early mining activity in the Cascades was directed toward exploration and development of these high-grade veins. The terrain and accessibility problems attendant with Cascade terrain precluded serious economic consideration of the lower grade disseminated deposits.

Many of the lode sulfide deposits occur in faults and shears paralleling the northwesterly regional trends. In those mining districts that are situated along the northeast-trending shear belts, however, many of the veins strike northeast.

Rock alteration associated with the lode sulfide occurrences is generally restricted to the areas immediately adjacent to the veins. Significantly, even in this type of metal occurrence, secondary orthoclase is commonly one of the principal silicate alteration minerals.

Contact deposits. — Few contact deposits in the Cascade Range are of economic significance. Hornfels aureoles surrounding the intrusive plutons seldom contain sulfides other than pyrite and (or) pyrrhotite. This lack of economic mineralization is due, at least in part, to the chemical incompatibility of the country rock. In a few isolated localities, replacement pods of massive sulfide minerals occur in limestone or marble.

Ross Lake Area — Eastern Whatcom County

The main prospect in this area is the Davis property (Fig. 21), situated on the north and south slopes of Silver Creek, 2 miles south of the Canadian border on the west side of Ross Lake. The mineralizing environment was somewhat unusual for the Cascade Range. A brief description of the area will demonstrate the fundamental principle of uniformitarianism as applied to Cascade sulfide occurrences. The host rock types may vary, but the overall structural and chemical environments retain remarkable similarities.

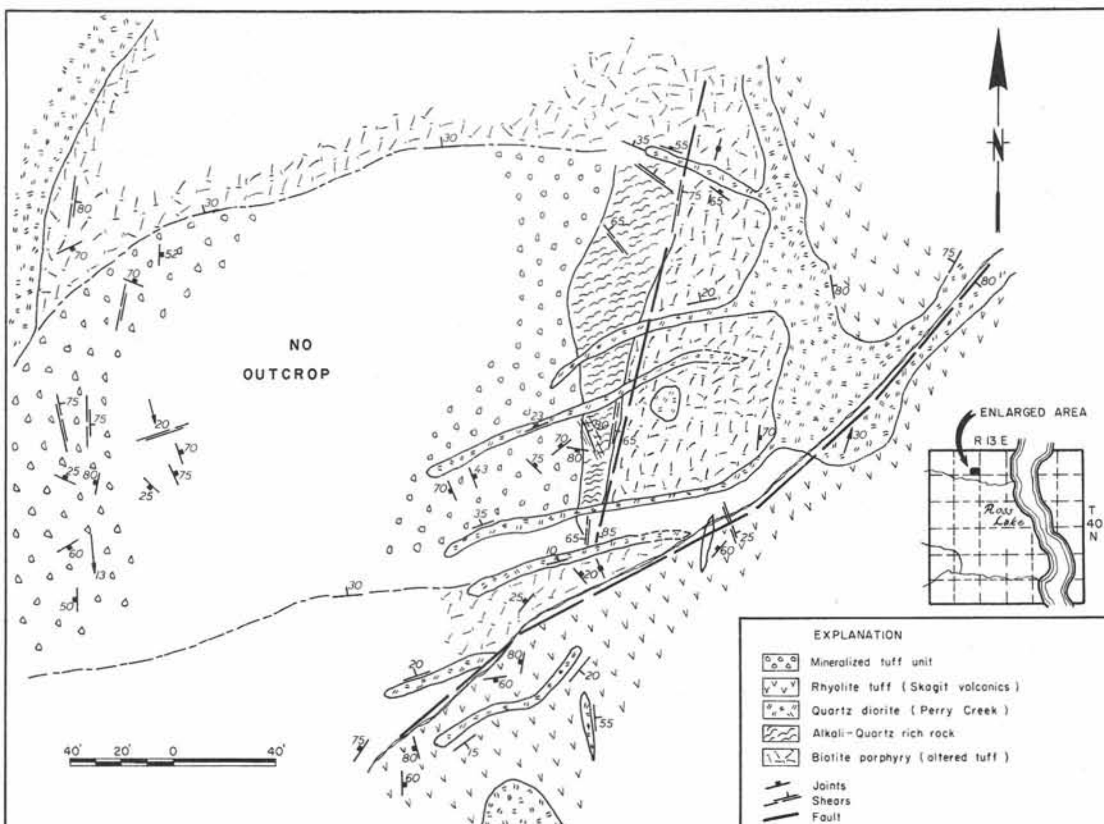

FIGURE 21. — Geologic map of Davis property, Whatcom County. Sec. 5, T. 40 N., R. 13 E.

Two rock types predominate in the Silver Creek drainage. The oldest rocks, named the Skagit Volcanics by Daly (1912), consist primarily of flows and tuffs ranging in composition from andesitic to rhyolitic and having dacites predominating. Local volcanic breccias have been mapped. In general, the older members of the Skagit Volcanics are composed of andesite flows. Up section, dacites, and finally rhyolites become more common. This up-section change from more basic to acidic composition suggests an origin of the volcanics from fractional differentiation of a common parental magma. The Skagit Volcanics are considered to be Oligocene (Daly, 1912 and Misch, 1966) in age. South and east of Silver Creek, Pennsylvanian-Permian eugeosynclinal sedimentary and volcanic rocks (Hozomeen Group) underlie the Skagit Volcanics.

The Skagit Volcanics are intruded by the Perry Creek phase of the Chilliwack composite batholith (Misch, 1966 and Shideler, 1965). Misch (1966) reported an age of 30 m.y. for the Perry Creek phase. Within this phase, quartz diorites and granodiorite predominate. In the eastern Silver Creek valley, the intrusive rocks show a considerable increase of K-feldspar content, resulting in the localized occurrence of quartz monzonite. Rare dikes and sills of granite appear to have been the product of late fractional crystallization of acidic differentiates within the parent magma.

Along the contact of the Perry Creek intrusive in the Silver Creek valley, the Skagit Volcanics have been hornfelsed in hornblende hornfels facies. Within the contact aureole the volcanics are extensively pyritized, resulting in the formation of large gossan zones. These areas are commonly leached to a shallow depth. Sporadic traces of chalcopyrite occur in these rocks.

Structurally, the prospect area has been subjected to several periods of deformation. The Skagit Volcanics strike east-northeast, dipping essentially in a homoclinal section to the northwest at inclinations of generally less than 45°. Faulting and shearing in the volcanics are of at least two ages. The oldest set strikes northwest and is cut off by a later north-northeast set. It is apparent that the degree of sulfide mineralization at the prospect is at least partly related to the earlier deformation in the volcanics.

Presently available data indicate that the main sulfide occurrences at the prospect are restricted to a northeast-striking and gently (±30°) north-dipping volcanic (probably dacite) tuff unit. The tuff has been brecciated and subjected to moderate to intense silica and potassium introduction. The introduced silica and potassium, as well as the later sulfides, appear to have utilized pre-existing structures as avenues for solutional transfer. The principal alteration minerals in the sulfide-bearing volcanic rocks are secondary biotite, quartz, and K-feldspar; there are subordinate amounts of chlorite, sericite, kaolin, carbonate, and epidote. Minor garnet (possibly grossularite) is present in the rare carbonate veins. Secondary biotite, quartz, and K-feldspar generally are most evident in the areas of high copper and molybdenite concentration. This association suggests a close relation between quartz-potassium introduction and sulfide deposition. The source of both the alteration solutions and the sulfides is thought to be the subjacent Perry Creek intrusive. Table 10 shows the general compositions of the Perry Creek rocks (granodioritic phase) and the mineralized tuffs in the prospect area.

Shallow supergene alteration has resulted in the development of a thin skin of quartz-sericite rock over the sulfide zone. Incipient leaching of the hypogene sulfides has also occurred near the surface. Sulfide mineralization within the volcanics consists primarily of chalcopyrite with subordinate molybdenite, pyrrhotite, and pyrite. The chalcopyrite occurs in veinlets, pods, and as disseminations. The molybdenite is mostly disseminated in the quartzo-feldspathic replacement material. The mineralized tuff member is truncated to the east by a N. 10° W.-striking post-mineral fault. The highest concentrations of copper and molybdenum are directly adjacent to this fault zone on its west side. This concentration of sulfides near the fault suggests that earlier fracturing or possible faulting was active along this zone.

On the south side of Silver Creek, molybdenite and minor chalcopyrite occur in a quartz-filled stockwork within the Perry Creek rocks. K-feldspar is a common gangue constituent in these veinlets. Sparse molybdenite also occurs along silicified joints in Perry Creek rocks exposed along the gorge of Silver Creek. Elsewhere in the Perry Creek intrusive, sulfide mineralization is rare. This absence of silfides is coupled with the general lack of alteration. The rocks are fresh except for regional incipient chloritization and sericitization.

TABLE 10.—Weight percent of the major oxides (calculated from modes) in the subjacent silicified Perry Creek intrusive (granodiorite) and the adjacent K-feldspathized volcanic tuff unit. Sulfide content not included in calculations. Davis prospect, Whatcom County

	Perry Creek intrusive (granodiorite) (two modes) (percent)	Feldspathized tuff (five modes) (percent)
SiO_2	75.5	68.9
Al_2O_3	13.8	17.9
Fe_2O_3	----	----
FeO	0.3	0.6
MgO	1.5	0.2
CaO	1.6	2.5
Na_2O	3.6	4.3
K_2O	2.6	5.3
H_2O	0.7	0.2
Totals	99.6	99.9

Several quartz diorite sills intrude the mineralized rhyolite tuff member. These sills postdate the sulfide mineralization and probably the Perry Creek intrusion. It is believed that the Perry Creek was the source of the introduced potassium and silica material as well as the sulfides in the volcanic rocks. If this is true, it indicates that mineralization and alteration were associated with late alkaline differentiation of the Perry Creek mass. The late sill rocks are mainly unaltered quartz diorite and carry only trace amounts of sulfide. They could be related to the late quartz dioritic phase of the Chilliwack batholith.

A summary of the probable geologic events leading to the present distribution of rock types and mineralization at the Davis prospect is presented below:

1. Deposition of Skagit Volcanics (probably upper Eocene).
2. Emplacement of the Perry Creek pluton and attendant hornfelsing and pyritization of the Skagit Volcanics.
3. Faulting and brecciation in the volcanics (tuff member).
4. Introduction, up-dip, of potassium and silica into the brecciated tuff.
5. Mineralization of the tuff member with pyrrhotite and (or) pyrite, chalcopyrite, and molybdenite in paragenetic sequence. Probably contemporaneous with this activity was the chalcopyrite and molybdenite deposition in the Perry Creek Quartz Diorite on the south side of Silver Creek.
6. Late shearing.
7. Emplacement of quartz diorite sills in the Skagit Volcanics.

The concentration of sulfide mineralization at the Davis prospect appears to have resulted from the combination of igneous activity, proper ground preparation in the form of transverse fracturing, and a high potassium environment. The type of host rock for the sulfides does not appear to be of particular importance as long as it is somewhat chemically compatible with the introduced material.

Buckindy Structural Belt—Skagit County

The Buckindy structure (Fig. 22), as previously discussed constitutes a first-magnitude transverse deformational belt that can be traced from the Darrington area on the western flank of the range northeastward for about 50 miles. Only a small,

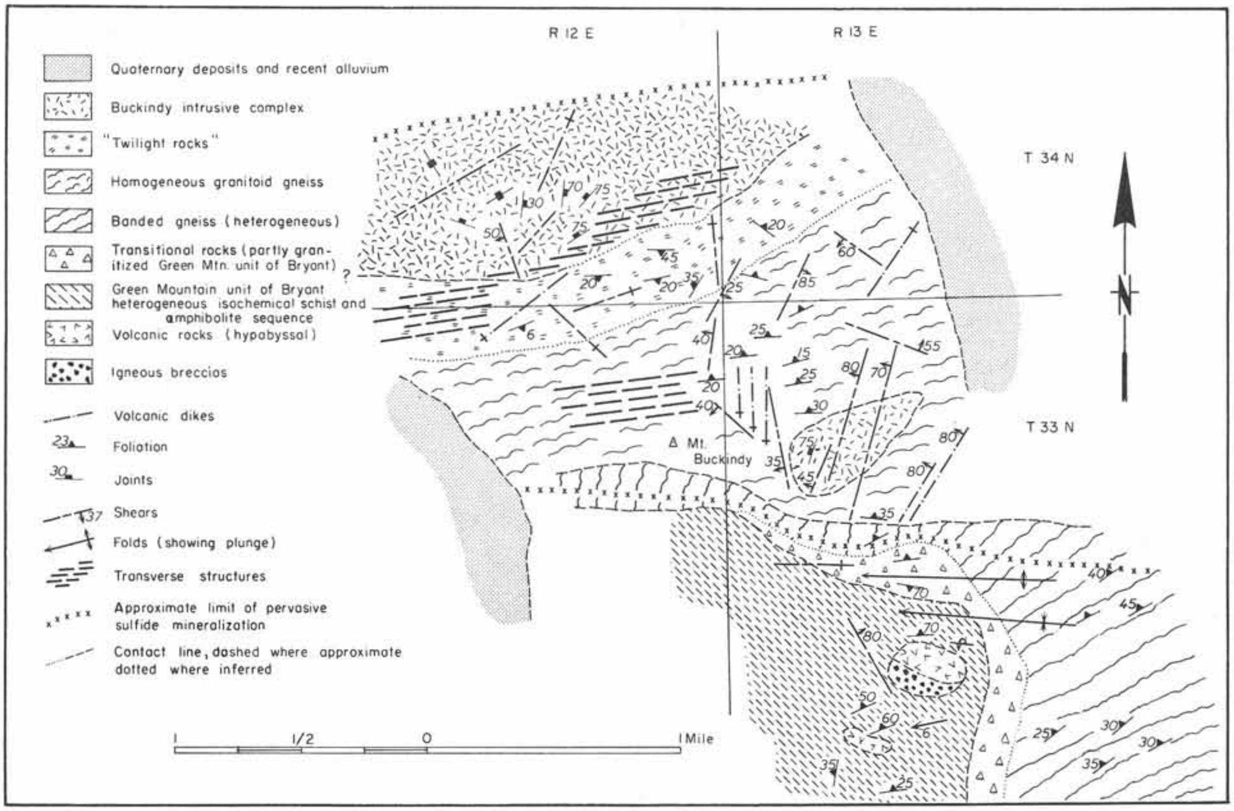

FIGURE 22. — Geologic map of the southeastern part of the Mount Buckindy massif, Skagit County. Data modified by A. R. Grant (1966) after Bryant (1955).

representative part of this structure, where it cuts the Mount Buckindy massif, is of concern here. The particular purpose of discussing this section is to illustrate the rather subtle environmental changes creating less than optimum conditions for sulfide concentration. In other words, in spite of the presence of a transverse structural system, some other physical factor that could have significantly changed the mineralization history was absent in the Buckindy area. The reader should be cautioned, however, not to interpret this as an attempt to pass final judgment on the Buckindy area. The zone comprises a large area of pervasive sulfide mineralization, and much more critical information should be acquired before any final evaluation can be considered reliable.

The predominant country rocks in the Buckindy area are biotite-hornblende migmatitic gneiss with intercalated schist and amphibolite layers (Bryant, 1955). Compositionally, the granitoid components of the migmatites range from trondhjemite to quartz monzonite. Post-kinematic potassium metasomatism, recorded by the presence of microcline and orthoclase, has been the most significant change responsible for the conversion of the calc-alkaline gneisses into the more alkaline varieties. Much of the foliation present in the gneiss is mimetic after schistosity formed during the synkinematic phase of Skagit metamorphism. Locally, advanced post-kinematic crystallization produced directionless granitoid rocks, but in most places some nebulitic remnants of earlier structure persist. Incipient mobilization has occurred on a local scale.

The migmatitic rocks grade northward into a relatively homogeneous mass of quartz diorite. When first studying the area in 1959, I thought this granitoid mass was somehow related to the Tertiary Cloudy Pass pluton, the northern part of which lies several miles southeast of the Buckindy area. However, further work revealed that these rocks probably were emplaced during a late stage of the Cascade metamorphic cycle as a result of mobilization and anatexis of the migmatitic gneiss units (Grant, 1966).

The following petrogenetic history for the Buckindy intrusive rocks is suggested:

1. Formation of the granitoid gneisses during the post-kinematic phase of the Cascade metamorphic cycle.
2. Partial fusion of the granitoid gneisses in the Mount Buckindy area, resulting in the production of a neomagma. The gneiss unit was not wholly assimilated in the neomagma, and partly reconstituted relics of the earlier rocks were thus preserved.
3. Incipient deformation of the incompletely crystallized mass.
4. Introduction of late potassic material.
5. Final solidification preceding the end of the Cascade metamorphic cycle. Minor thermal upgrading took place at this time, resulting in the formation of actinolite after retrogressively formed chlorite.
6. Post-Cascade cycle deformation accompanied by minor recrystallization.
7. Tertiary hydrothermal alteration.

Major differences exist between the Buckindy intrusive rocks and those of the Cloudy Pass batholith. The Cloudy Pass has sharp intrusive contacts, is undeformed (except for minor localized shearing), and contains a wholly igneous suite of minerals.

Structurally, the planar schistosity in the metamorphic rocks trends east-west, apparently in response to the east-trending re-entrant structure, which has been mapped southeast of Mount Buckindy (see under Transverse Structural Belts). Open folds, the axes paralleling the east-west trends, are superimposed on the earlier metamorphic structures. En echeolon sheeting and shearing, trending east-west to northeast-southwest, are the predominant fracture patterns. This, of course, represents the passage of the transverse structure system. No well-developed complementary fracture set was mapped.

Sulfides occur ubiquitously in the Buckindy area, yet nowhere were they observed to be in significant concentrations. Pyrite and pyrrhotite are the principal sulfides, mostly present in small crosscutting veinlets. Locally, chalcopyrite and traces of molybdenite occur, but never in substantial quantities. Several quartz-sericite altered pluglike masses of granite are present along the contact of the intrusive rocks and migmatites. These masses, commonly containing small amounts of chalcopyrite, occur along strike of the axial planes of two open anticlines in the metamorphic rocks.

The fracture-filling sulfide occurrences are not restricted to any particular pattern. Rock alteration is sporadic. In general, no definitive distributional patterns of either sulfides or wall rock alteration are recognized in the Buckindy area. A partial answer for this apparent lack of significant sulfide concentration may be found in the differences of the areal environments on Mount Buckindy as compared with other zones of probably greater sulfide concentration.

In the earlier sections of this paper, an attempt has been made to show the relations between sulfide mineralization and the physical-chemical environments. It has been clearly demonstrated that transverse structures, structural intersections, and late magmatic alkaline activity (as related to mostly Tertiary granitic evolution) do definitely have a significant bearing on sulfide deposition. In the Buckindy area, the transverse structures are present but the other possible catalysts are noticeably absent; for example:

The Buckindy intrusive rocks predate the later cycles of igneous activity. They were emplaced during regional metamorphism as a climaxing event of granitization. Wholly igneous processes of magmatic differentiation have not fully evolved. Therefore, concentrations of potassium-silica rich material in the late intrusive cycle may not have taken place, at least in a manner similar to that occurring in the Tertiary intrusions.

Structural data do not outline any complementary fracture system that could possibly serve as an intersection point for the east-west belt. Even the folds in the metamorphic rocks parallel the transverse trends.

Such factors could well contribute to a less favorable environment for sulfide deposition at Buckindy.

Eastern Section of the Glacier Peak Structural Belt—Snohomish and Chelan Counties

The Glacier Peak structural, as already mentioned, is the largest known transverse shear zone in the Cascades. The western end of the structure, in the Sultan Basin-Silver Creek-Vesper Peak areas, is discussed separately. The eastern section

(Fig. 23), crosscutting the metamorphic-plutonic core of the range, has strongly influenced the positioning of several significant sulfide occurrences, including the copper deposits on Miners Ridge and those in the Holden mine area.

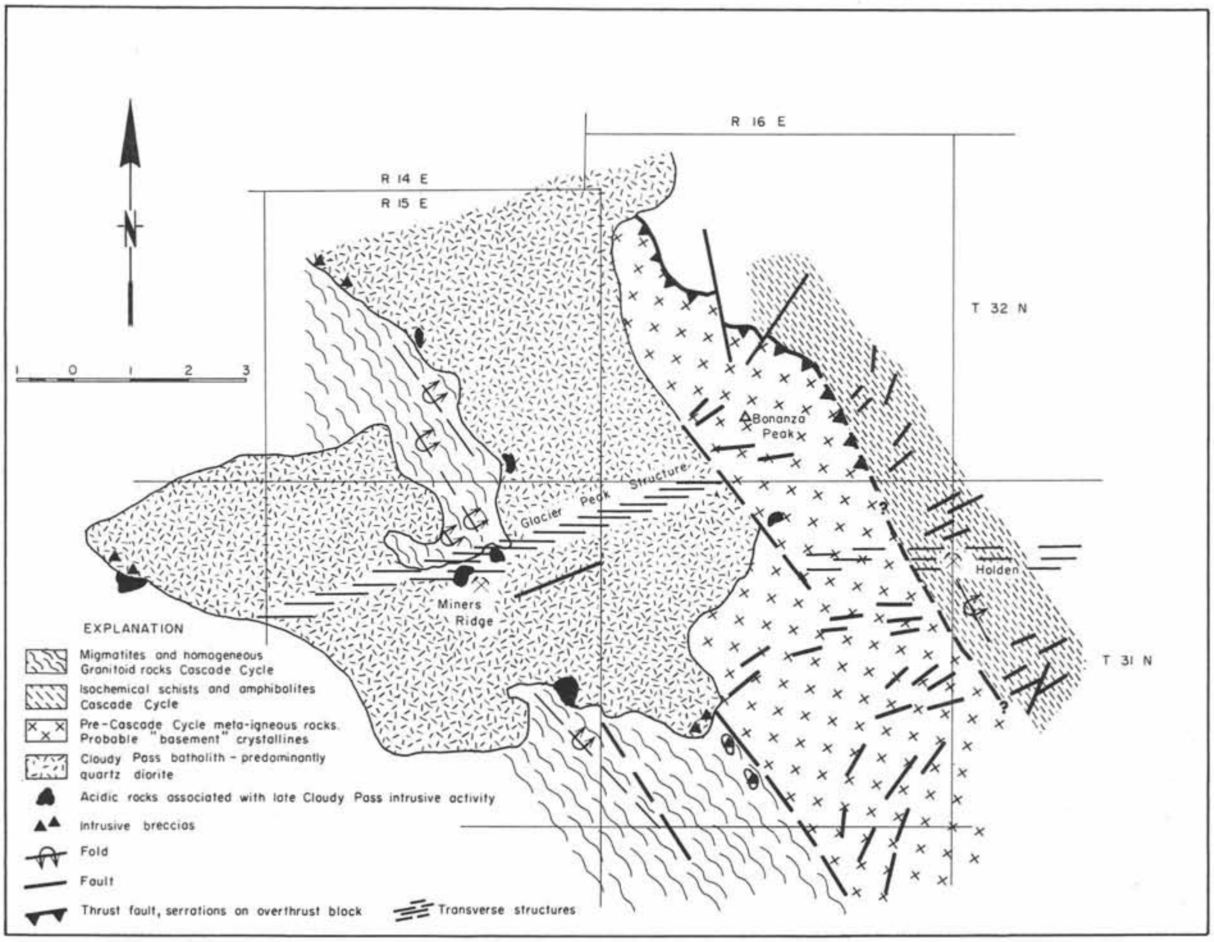

FIGURE 23. — Geologic sketch map of the eastern section of the Glacier Peak transverse structural belt, Snohomish and Chelan Counties. Data partially from Ford (1959) and Cater and Crowder (1956).

A considerable amount of detailed information has already been presented regarding the structural and chemical environments in the vicinity of the Miners Ridge ore body. It is the intent here only to present a regional analysis of this area and to outline briefly the significant physical and chemical controls for the distribution of the various sulfide occurrences.

The oldest rocks in the Miners Ridge area consist of a heterogeneous migmatitic complex. The original parent rocks of these migmatites are thought to have been eugeosynclinal sediments and volcanics of questionable Paleozoic age, which, in turn, were synkinematically metamorphosed, essentially in a medium-grade isochemical environment during the Cascade metamorphic cycle, into mica-schists, para- and ortho-amphibolites, and subordinate quartzite and marble. Syn- and post-kinematic alkali and silica metasomatism, combined with local mobilization, converted the isochemical rocks into migmatitic and granitoid gneisses. In all probability, metamorphic differentiation was not responsible for the heterogeneity of this complex; therefore the primary control must have been a function of the variability of the original chemical composition of the parent material.

It is probable that during the early Late Cretaceous orogenic cycle some distributed shearing occurred in these gneissic rocks. Thermal metamorphism and recrystallization associated with the Tertiary emplacement of the Cloudy Pass pluton probably destroyed many of these earlier cataclastic effects.

East of Miners Ridge, toward Holden, the migmatitic gneiss complex is in tectonic contact with a northwest-southeast-trending belt of pre-Cascade metamorphism quartz diorite plutonic rocks, which were subsequently converted, during the Cascade cycle, into tectonized meta-quartz diorite. These rocks were overthrust to the northeast over isochemical schists and amphibolites of Cascade metamorphism age. The Holden mine is situated within the eastern isochemical belt, in predominantly amphibolite and hornblende-biotite schist terrain.

All the aforementioned rock units were intruded by the Tertiary Cloudy Pass pluton. The Cloudy Pass pluton is a composite batholith, having at least three intrusive phases: (1) an early pyroxene diorite phase, (2) a main-phase quartz diorite, and (3) a late deuterically altered potassium-rich phase. The petrology of these rocks has been discussed in the section on Late Cretaceous-Tertiary intrusive activity. Repetition of these details beyond emphasizing the significance of the acidic differentiates as related to the Miners Ridge copper deposits is unnecessary. (Chemical composition data on the Cloudy Pass rocks is shown in Table 5, on page 56.)

The gross structural features in the Miners Ridge-Holden area involve the intersection of northwest-trending structures and the transverse Glacier Peak structural belt. In the Miners Ridge area the main sulfide deposits occur at the intersectional point of the east-west en echelon sheeting in the batholithic rocks and the axial projection of a series of overturned anticlines in the roof pendant metamorphic rocks. These folds were recognized in the field by mapping the repetition of relic layers of muscovite schist, biotite paragneiss, and quartzite. Extreme crumpling and shearing has occurred along the northwest-trending axial planes of the anticlinal structures.

From the Miners Ridge area, the Glacier Peak structural belt strikes east-northeast for several miles through Cloudy Pass rocks. At the eastern contact of the batholith, the transverse structures are truncated by a northwest-trending high-angle fault. The fault has displaced the northeastern block to the southeast in a general strike-slip pattern. Therefore, the southeast-faulted easterly continuation of the transverse belt is found to pass through the Holden mine and eventually across Lake Chelan, to become the primary structural control for the sulfide deposits in the Meadow Creek area.

The structural environment in the Holden mine area is perhaps as classical as any in the Cascades for the distributional control of sulfides. Elsewhere in the range, it has been demonstrated conclusively that sulfide deposition is closely related to intrusive activity and transverse belts of deformation. At Holden, however, the ore deposition appears to have occurred before the intrusion of the Cloudy Pass pluton and, in fact, seems more related to the Cascade metamorphic cycle. This, of course, makes the Holden deposits somewhat unusual.

DuBois (1954) studied the Holden mine area in detail. He noted, as had earlier workers, the concentration of sulfides along the axial zone of a small overfold in the predominantly ortho-amphibolite terrain. He was also able to demonstrate that the ore body is situated in a localized zone of high-grade metamorphism, whereas the surrounding regional metamorphic grade corresponds to andesine-epidote-amphibolite facies (upper medium-grade). DuBois further noted the almost complete absence of hydrothermal alteration in the mine zone. Post-ore quartz diorite dikes, of probable Cloudy Pass origin, transect the sulfide zones. From these data, DuBois suggested that metallization was synchronous with high-grade metamorphism during the Cascade cycle and that the sulfides were concentrated in the axial zone of the pre-existing overfold as a result of metamorphic processes.

The possible pre-Tertiary age of the Holden ore body gives rise to some interesting speculations as to the structural setting. As has been shown, the transverse structural belts cut all pre-Pleistocene rocks. This, of course, establishes an upper limit to the age of deformation. It is also known that relatively young intrusions such as the Cloudy Pass (± 22 m.y.) are transversely deformed. Thus, it can be readily demonstrated that the latest stage of deformation was post-early Miocene and pre-Pleistocene. It cannot be ascertained, however, whether the late Tertiary transverse movements represent the main period of crosscutting forces or whether they represent the latest episode along an older system. In other areas, certain relations suggest transverse movements before the Tertiary intrusion. As previously suggested, the northeast-trending Buckindy structures may have, in part, controlled the emplacement of the transverse elongate Cascade Pass pluton, which is thought to be a satellitic stock of the Cloudy Pass pluton. In the Sultan Basin-Silver Creek area, northeast-trending sheet jointing in the Swauk Formation was forcefully bowed out as a result of the emplacement of the Snoqualmie batholith. These rather scattered observations suggest activity along some transverse deformational belts prior to the Tertiary period of intrusion. In the Holden area, with evidence pointing to metallization during the Cascade metamorphic cycle, one can only speculate as to the pre-Tertiary existence of the Glacier Peak structural belt.

As a result of mapping in the Holden quadrangle (Cater and Crowder, 1956 and Crowder, 1959), strong east-west- to northeast-southwest-trending shear activity in the Holden mine area can be shown. In fact, the general impression gained from these maps suggests that the regional northwest shearing patterns, which are so evident both south and north of Holden, swing to the northeast in the vicinity of the mine as if responding to transverse stresses. These structural trends are also evident on DuBois' (1954) detailed maps of the mine area. Although no definite age can be established for the period of transverse shearing in the Holden area, much of it may have been associated with regional metamorphism. It would be logical to assume that some type of structural couple was present in the Holden area during the period of metallization, and the most likely couple may have been the northwest-trending folds and the northeast-trending shears.

Along the southern contact of the Cloudy Pass pluton (Red Mountain-Chiwawa area), numerous intrusive breccias were mapped by Morrison (1954). Several of these breccia zones contain substantial amounts of sulfide. They are aligned in a general north-south direction and commonly break the contact between the older metamorphics and the subjacent intrusion. The breccia fragments include gneiss, schist, amphibolite, diorite porphyry, quartz diorite, and granite-quartz monzonite. Petrographic studies of the granite fragments indicate them to be similar mineralogically and genetically (of deuteric origin) to the granite occurrences at Fortress Mountain. The incorporation of granite as fragments in the Red Mountain breccias suggests that a deep-seated zone of sulfide-bearing, deuteric and hydrothermally altered potassium-rich rock could exist in this area.

For other pertinent structural and chemical data concerning this part of the Glacier Peak structural belt, particularly in the Miners Ridge-Fortress Mountain areas, the reader should refer to those sections of this paper dealing with transverse structural belts, structural intersections as related to sulfide deposition, and wall rock alteration. In general, it can be clearly demonstrated that in this segment of the range there is an important relation between metallization and Tertiary intrusive activity, transverse deformation, and potassium alteration. Holden represents the one major anomaly in this overall scheme.

Sultan Basin-Silver Creek—Snohomish County

The Sultan Basin-Silver Creek area (Fig. 24) is situated along the western flank of the North Cascades in the Mount Baker National Forest (Tps. 28 and 29 N., Rs. 10 and 11 E.). The oldest rocks in the district are probable late Paleozoic volcanic and sedimentary eugeosynclinal rocks, possibly correlative with the Chilliwack Group. Overlying the Paleozoic section is a thick sequence of weakly metamorphosed Jurassic-Cretaceous sedimentary rocks. Both the Paleozoic and Mesozoic rocks were involved in the early Late Cretaceous overthrusting. West of this area, an extensive zone of phyllitic rocks appears to tectonically overlie the Paleozoic and Mesozoic sections, suggesting the southward continuation of the Shuksan thrust belt. Unfortunately, detailed mapping of this area is not available at this time (1967).

Several ultramafic dikes intruded the Jurassic-Cretaceous rocks. Farther east, ultramafic rocks cut the Swauk Formation. The ultramafic rocks, consisting predominantly of serpentinized peridotites, may have been emplaced along older, relatively deep-seated structures. Spotty sulfide occurrences are present along the contact between the ultramafic dike complex and the Snoqualmie intrusive rocks in the Sultan Basin area.

The Late Cretaceous-Paleocene Swauk Formation rests unconformably on the older rocks. Steep open folding of the Swauk rocks, their fold axes paralleling the northwest regional trends, is attributed to the moderately strong early Eocene deformation. The Barlow Pass Volcanics of probable late Eocene-early Oligocene age unconformably overlie the Swauk Formation. They are primarily flows, predominantly andesite with subordinate rhyolite and dacite. Interbedded arkosic sediments

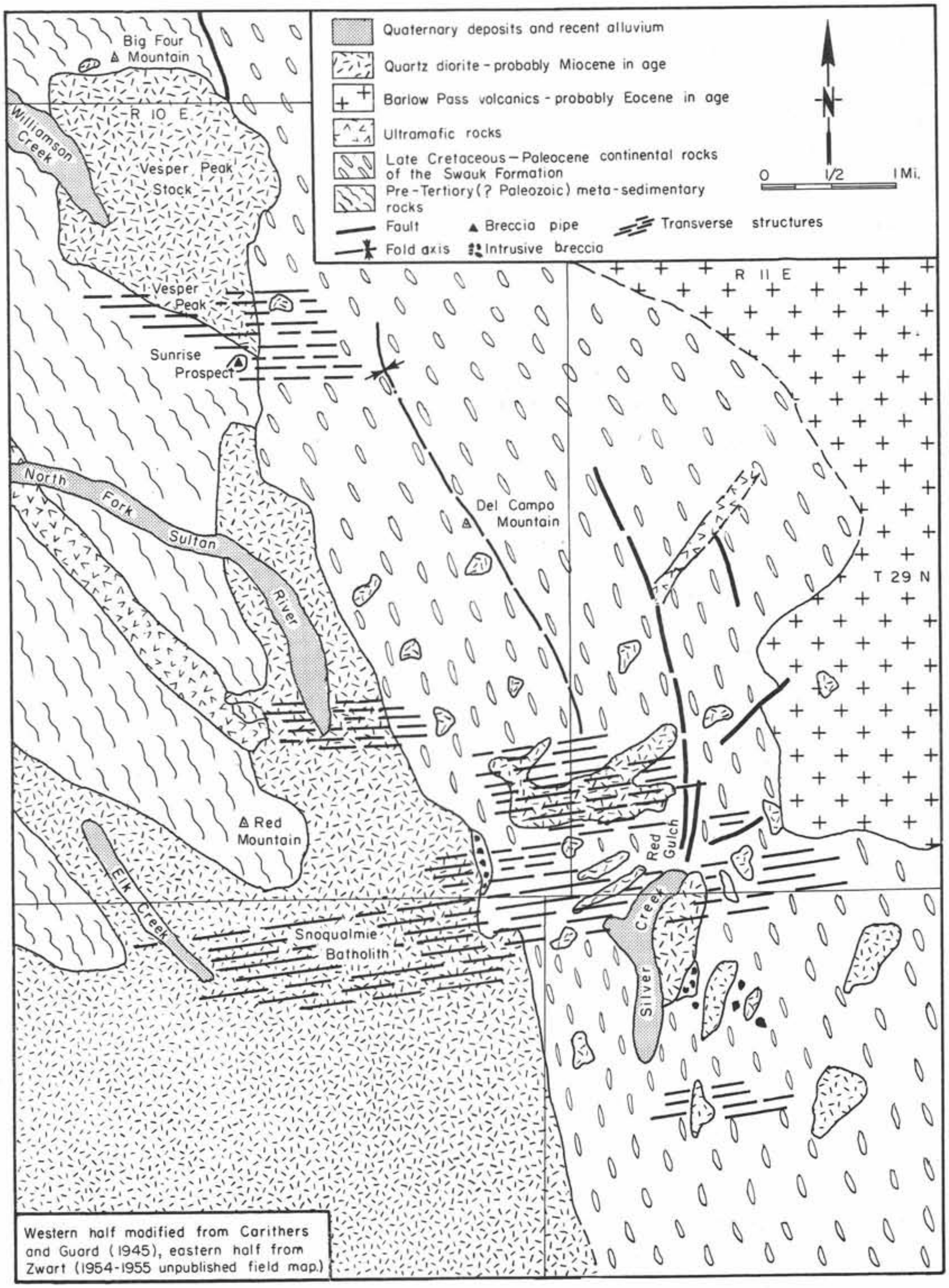

FIGURE 24.—General geologic map of the Sultan Basin, Vesper Peak, Silver Creek areas, Snohomish County.

are common in the Barlow Pass unit. The volcanic rocks were mildly folded, probably in middle Oligocene time. Culminating the Tertiary history in the area was the emplacement of the middle Tertiary Snoqualmie batholith. North of the main batholithic mass, the satellitic Squire Creek stock invaded the Tertiary and pre-Tertiary rocks. The eastern part of the area (east of Silver Creek) is intruded by the Grotto batholith, which is believed to be an early, more mafic-rich phase of the

Snoqualmie intrusive cycle. Further reference in this report to the intrusive rocks, regardless of probable phase relations, will be all-inclusive under the term "Snoqualmie." This period of granitic evolution set the stage for the post-intrusion shearing and mineralization.

Structurally, the area is complex. Pre-Tertiary deformational cycles are numerous but apparently of little importance in the influencing of later sulfide depositional patterns. The northwest-trending folds in the Swauk sedimentary rocks have been subjected locally to axial plane shearing, as exhibited in the Red Gulch anticline on Silver Creek, where a small reverse fault downdropped the eastern block. Most of the axial plane shears are of small magnitude. The N. 15° W.-trending Del Campo fault can be traced northward across the South Fork of the Stillaguamish River into the ultramafic dike zone in the Devils Peak-Jumbo Mountain area. Shearing paralleling Swauk bedding planes appears to be an adjustment feature contemporaneous with Swauk folding.

North of Barlow Pass and the South Fork of the Stillaguamish River, a sharp reversal in the trends of the fold axes in the Barlow Pass Volcanics of Vance, from N. 15° W. to N. 35° E., is well displayed. Although the elbow of this apparent structural warp is faulted, it is possible that this "re-entrant" may have significantly influenced the positioning of the major east-west sulfide deposition control structures in the Sultan Basin-Silver Creek area to the south and in the Helena Peak area to the north.

The major structural patterns, which appear to have most significantly controlled the pattern of sulfide distribution, are confined to a general east-west en echelon shear-fracture system varying in strike from N. 65° W. to N. 60° E. This structural belt is considered to constitute the western end of the Glacier Peak structure. Certain field evidence suggests that the transverse stresses were active prior to the emplacement of the Snoqualmie batholith. Northeast-trending jointing and minor shearing in the Swauk Formation appears to have been bowed out locally 20° to 30° (from northeast to southeast) by the apparent forceful intrusion of the Snoqualmie pluton. Further evidence for forceful intrusion is indicated by displacement of bedding plane strikes in the Swauk strata adjacent to the intrusive contact. Figure 25 illustrates these general relations.

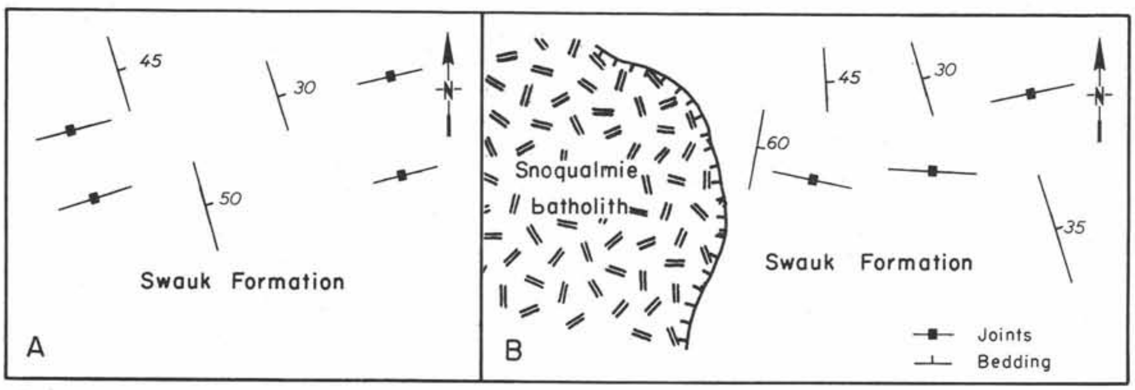

FIGURE 25. — Diagrammatic sketch showing proposed evidence for forceful intrusion of the Snoqualmie batholith in the Sultan Basin area, Snohomish County. Swauk Formation structures have been displaced.

A. Prior to Snoqualmie intrusion.

B. After Snoqualmie intrusion.

Following the emplacement of the Snoqualmie plutonic rocks and the solidification of the peripheral intrusive zone, recurrent deformation paralleling the earlier east-west system produced a strong east-west joint pattern in the quartz diorite. The complementary north-south joint pattern is less well defined. A second set of N. 80° E.-striking joints was superimposed on the earlier joint sets in the Swauk Formation. Local shearing, paralleling the master fracture pattern, was perhaps guided by the pre-existing joint system. Many of these shears, as well as the master joints, served as avenues for solution migration during the period of sulfide deposition. Post-mineralization shearing, predominantly in a northwest direction but locally recurrent along east-west trends, is relatively common.

Several miles north of the Sultan Basin-Silver Creek district, in the Helena Peak area, a fracture pattern similar to that just described developed in the southeastern corner of the Squire Creek stock. Menzer (1966) tabulated the distribution of joint patterns in the stock adjacent to its upper contact with the Swauk Formation. Well-developed northwest and northeast sets are present, but over 80 percent of the mineralized joints are those trending east-northeast. The mineralized joints, according to Menzer, are tensional structures transverse to the northwest-elongated pluton.

Within the Sultan Basin-Silver Creek area, most of the sulfide mineralization is confined to the contact aureole of the intrusion. Intrusive breccias, occurring sporadically along the plutonic contacts, commonly are sparsely mineralized. Disseminated sulfides are not common in the intrusive rocks except in those areas where intense ubiquitous hydrothermal alteration has preceded sulfide deposition. Tensional openings at intersections of the approximate east-west structural system and complementary north-south structures commonly are loci for sulfide concentrations. In general, however, sulfides occur in the north-south fractures for only a short lateral distance from the point of intersection with the transverse structures.

Alteration of the intrusive rocks is highly variable and apparently is in part related to the intensity of fracturing. Potassium alteration, particularly in the form of secondary biotite and K-feldspar, is noticeably absent in most areas. At best, it occurs sporadically, adjacent to chalcopyrite veins. This relation is best exposed in the Elk Creek area south of the Sultan Basin, where pink orthoclase is common in the widely distributed chalcopyrite veinlets but is considerably less common in the quartz diorite country rock. Adjacent pyrite veins contain no recognizable K-feldspar. Elsewhere in the intrusive rocks of this district, the "typical" alteration profile is of moderate intensity. Adjacent to the sulfide zones, plagioclase has been albitized, mafics chloritized, and feldspars sericitized. Both clinochlore and pennine are present, but clinochlore predominates. Secondary biotite occurs mostly after hornblende; only rarely does it occur in the main rock fabric, and, indeed, the intensity of secondary biotite crystallization is so weak that much primary hornblende is still preserved.

Sulfide mineralization in this area is multicyclic. At least three stages are recognized. The earliest stage, possibly related to the deuteric alteration phase of the intrusive cycle, consisted of minor chalcopyrite and pyrrhotite deposition. The second stage, related to hydrothermal activity that postdated the solidification of the intrusive periphery, was responsible for complex sulfide mineralization including, in approximate paragenetic sequence from youngest to oldest, molybdenite, pyrite, pyrrhotite, galena, sphalerite, chalcopyrite, and bornite. Within the district there there is a crude base metal zonational pattern having a central core of copper-molybdenum surrounded by a peripheral zone of lead and zinc. The third stage, restricted to late cross-cutting fractures, produced minor pyrite, orpiment, and realgar.

Northwest of the Sultan Basin, in the Vesper Peak area, some rather noteworthy sulfide occurrences are present. Here, a small satellitic intrusion of the Snoqualmie batholith, named the Vesper Peak stock, invaded pre-Tertiary metasedimentary and Paleocene Swauk Formation rocks. Near the southeastern contact of the stock, a small breccia pipe occurs at the Sunrise prospect. The pipe is crudely elliptical and steep walled, and at least part of it is believed to have formed prior to the emplacement of the adjacent stock. This initial development may have been related to one of the earlier intrusive phases of the Snoqualmie batholith that either is not exposed or was obliterated by later intrusive activity.

The fragments in the breccia consist of three different lithological units, the most predominant being argillite in which traces of graded bedding are still preserved. Siltstone and graywacke fragments are subordinate. All of the rocks comprising the breccia fragments were subjected to intense hornfelsing, which presumably was contemporaneous with the emplacement of the Vesper Peak stock and prior to the development of the pipe. The hornfelsing reached lower medium-grade, as was evidenced by the development of muscovite rosettes and fine-grained biotite. Quartz was subjected to complete recrystallization. As the temperature dropped, the graywacke fragments underwent extensive hydrothermal alteration, the earlier mafics being partly chloritized to pennine.

Two stages of quartz introduction occurred. The earlier, pre-hornfels stage was very minor, amounting to less than 5 percent of the total volume of the rock. This quartz subsequently was recrystallized in the hornfels environment. The second stage of quartz introduction (post-hornfelsing), seems to be related to the main period of sulfide deposition. Local replacement of some of the more siliceous fragments by the quartz is common.

Two generations of sulfides have also developed. The first stage (disseminated pyrite and questionable magnetite) may have been related to the hornfelsing. The second, more important stage appears to be associated with the late quartz. Pyrite is earlier, being replaced by later chalcopyrite. Locally, pyrite and chalcopyrite have incipiently replaced some of the more basic argillite fragments. Molybdenite deposition definitely appears related to late quartz introduction.

Two stages of post-breccia deformation are recognized. Minor distributed shearing took place prior to the final emplacement of the Vesper Peak stock. These shears later were partially filled with quartz that was subsequently recrystallized during hornfelsing. Post-intrusive, east-west sheeting cut the country rock, the breccia pipe, and the adjacent stock. Quartz and sulfides are common along these structures.

Two miles northwest of the Sunrise breccia pipe, in the central part of the Vesper Peak stock, several dikes (10 to 50 feet wide) of granite porphyry contain disseminated chalcopyrite and traces of molybdenite. The dike material appears to be late, potassium-rich differentiates of the pluton and suggest the possibility of a central core of this type of material.

Petrographically, quartz (15 percent) occurs as subhedral-anhedral phenocrysts. Relics of plagioclase (< 10 percent) are mostly sodic oligoclase. Minor pennine and traces of epidote probably reflect the earlier presence of mafic minerals. The matrix consists primarily of fine-grained K-feldspar, locally replacing plagioclase.

In summary, the Sultan Basin-Silver Creek district presents a wide variety of mineralization environments. Structurally, the area has been well prepared. Widespread intrusive activity has taken place. Of critical significance, however, is the lack of extensive potassium alteration in the sulfide areas. This basic fact could partly explain the spotty distribution of the sulfides and the absence of any known significant zones of concentration.

Index District—Snohomish County

This district is structurally similar to the adjacent Sultan Basin-Silver Creek district to the north. The Snoqualmie batholith intrudes a variety of country rocks ranging from upper Paleozoic and Mesozoic sedimentary rocks to lower Tertiary continental rocks of the Swauk Formation.

A southerly counterpart of the Glacier Peak structure; namely, an en echelon system of east-west to northeast-southwest shears, cuts all rocks of the area. Most of the sulfide occurrences are of the simple lode type, but even so, they show both alteration and structural characteristics similar to those of some of the more complex metalliferous districts in the range.

The lode deposits do not display the broad alteration halos that occur around some of the larger disseminated sulfide zones in other districts. However, the alteration assemblage of silicate minerals is similar. Orthoclase and (or) secondary biotite commonly occur adjacent to or within the areas of high copper concentration. Within the high-grade vein complex of bornite and chalcopyrite at the Sunset mine, orthoclase is a common gangue mineral in the ore shoots. A weak K-feldspar halo is present in the wall rock for several hundred feet adjacent to the main vein complex.

The principal sulfide veins show considerable variation in strike but basically can be divided into two main groupings—the northwest and the northeast systems. Weaver (1912) mapped the trends of the major vein systems; a synopsis of these trends is shown on the strike diagram in Figure 26. Of the 19 principal veins mapped at the various prospects, 13 strike in the northeast quadrant and 6 strike northwest. This preponderance of northeast systems is influenced principally by the east-west sheeting zones. The complementary northwest veins mostly parallel the regional grain of faulting and shearing. Yet the northwest structures are mineralized only in those areas in which they intersect with northeast shears. This relation strongly suggests that the primary structural control for sulfide deposition in this area is the intersection of northwest- and northeast-trending shear systems.

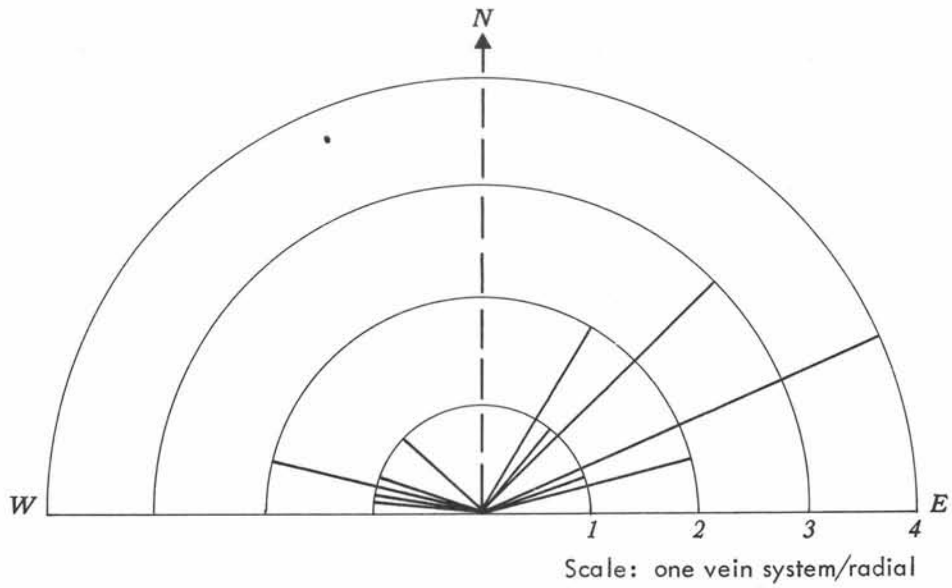

FIGURE 26.—Strike diagram of the principal vein systems in the Index mining district. Adapted from Weaver (1912).

Quartz Creek Area—King County

The Quartz Creek area (Figure 27), in the Snoqualmie National Forest, is about 15 miles north of the small community of North Bend, on U.S. Highway 10.

The prospect area is close to the western contact of the middle Tertiary Snoqualmie batholith. Pre-Snoqualmie rocks include the Mesozoic Calligan Formation (probably correlative with Misch's Nooksack Formation), consisting predominantly of eugeosynclinal graywackes, shales, and subordinate conglomerates. Erosional remnants of probably Eocene volcanic rocks occupy a roof pendant position relative to the batholithic rocks. Tentatively, these rocks are correlated with the Naches Formation, but they have been informally named the Mt. Garfield volcanics by Bethel (1951).

Intrusive rocks in the Quartz Creek area are complex. Bethel first recognized the intrusive complexity in the Quartz Creek region, but failed to establish the proper intrusive chronological relations. Recent work by Howard (1967) and by Erikson (written communication, 1967) in the Quartz Creek region have established the following intrusive episodes (from oldest to youngest):

1. Emplacement of fine-grained dioritic rocks.
2. Emplacement of the Preacher granite (originally mapped and informally named by Bethel, 1951). This mass predated the Snoqualmie intrusive cycle. Its proper petrogenetic relation in the overall Tertiary period of granitic evolution in the Cascades is not fully understood. Erikson's work should substantially clarify this problem.
3. The earliest intrusive episode in the Snoqualmie cycle was the emplacement of the Quartz Creek stock, originally mapped and informally named by Howard (1967). This small mass consists predominantly of porphyritic diorite and subordinate quartz diorite. Most of the significant sulfide deposits in the area are within the Quartz Creek stock.
4. Main-phase quartz dioritic of the Snoqualmie batholith.
5. Quartz monzonites. These rocks appear to represent acidic differentiates that characterize the end of the Snoqualmie intrusive cycle.

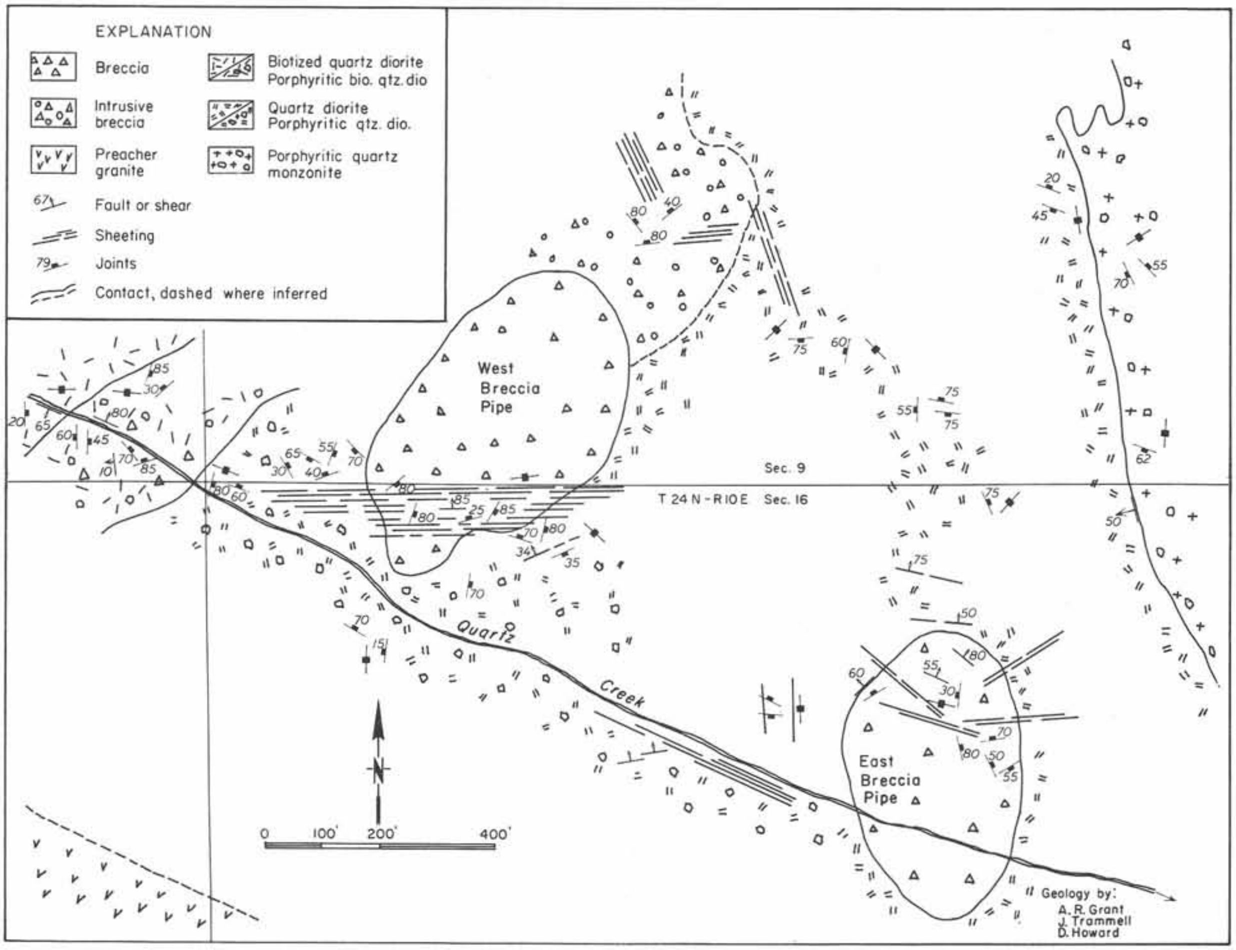

FIGURE 27. — Geology of the Quartz Creek property, King County, Wash.

The sulfide occurrences are restricted mainly to a series of breccia zones within the Quartz Creek stock. Breccias of various types and geometrical configurations abound in the intrusive complex, but those of particular economic significance are steep-walled, crudely ovate breccia pipes. The contacts of the pipes with the country rock are sharp. Most of the breccia fragments are angular, ranging in size from 1 inch to a general maximum of 6 inches. Several large "horstlike" blocks of quartz diorite have been mapped in the breccia, but these appear to be rare. The principal matrix material is composed of quartz and subordinate sulfides.

Alteration within the pipes is complex. Secondary biotite is ubiquitous, initially forming at the expense of primary hornblende and later crystallizing as a pervasive felty mat. Reddish-brown (Z) pleochroism characterizes the secondary biotite, as opposed to chocolate brown on Z in the primary magmatic biotite. Only traces of K-feldspar are present. Coincident with the high-sulfide zones, intense chlorite-sericite alteration is superimposed over the original alteration assemblage. In these zones, biotite has been completely chloritized, mostly to pennine but locally to clinochlore. Feldspars are strongly saussuritized, epidote and sericite being the principal alteration products. Locally, in replacement lenses within the easternmost breccia pipe occurrence, anthophyllite is present. Tourmaline commonly occurs adjacent to or within the high-sulfide zones. In the area as a whole, a close relation between the intensity of wall rock alteration and the magnitude of deformation and cataclasis is obvious.

The breccia pipes are elliptically elongate in a general north to northeast direction. Of particular structural significance is the predominant east-west sheeting and shearing system cutting the mineralized zones. Characteristically, the structures are en echelon in pattern. A subordinate structure set, trending northwest and steeply inclined to the southwest, intersects the east-west system.

Sulfide mineralization is relatively complex in the breccia zones, showing considerable variability. In the easternmost breccia pipe, sulfides occur in replacement lenses and in the breccia matrix. In some of the lenses, pyrite and chalcopyrite are the principal sulfides; in others, pyrrhotite and chalcopyrite predominate. Generally, pyrite and pyrrhotite are mutually exclusive, suggesting separate, though related, mineralizing cycles. Pyrite predominates in the breccia matrix.

Several hundred feet west of the east pipe, another breccia occurrence is characterized by the sulfide association pyrrhotite, arsenopyrite, and chalcopyrite. The sulfides are present as disseminations and in veinlets, and are much more uniform in distribution than are the erratic sulfide occurrences in the east pipe. The areas of highly disseminated sulfides are coincident with areas of intense hydrothermal alteration, particularly chloritization and sericitization. This relation seems to indicate the direct association between alteration and sulfide mineralization via similar channelways. The zone of sulfides dies out to the west, recurring again in localized areas of incipient to moderate brecciation along the general east-west fracture system.

Middle Fork Snoqualmie River Area— King County

The Middle Fork area (Fig. 28) is in eastern King County (Tps. 22 and 23 N., Rs. 11 and 12 E.),in the Snoqualmie National Forest. Rugged, subalpine mountainous terrain is characteristic. Tertiary rocks predominate in the Middle Fork area. The Naches Formation, consisting primarily of epiclastic volcanic rock, andesite flows, and breccias containing subordinate intercalated sedimentary strata, is intruded by the Snoqualmie batholith, of Miocene age.

Extensive thermal metamorphism along the intrusive contact has produced low- to medium-grade hornfels. Lower grade alteration in the volcanic rocks includes saussuritization of plagioclase and actinolite crystallization. Adjacent to the contact the andesite flows have been converted to incipiently feldspathized ortho-amphibolites. Pyritization in the volcanic rocks is restricted to the contact aureole. Intrusive brecciation along the contact of the Naches Formation and the Snoqualmie batholith is well exhibited in the upper Burnt Boot drainage. The intrusive contact dips gently to the southeast.

Granitic rocks of the Snoqualmie batholith within the Middle Fork area include lithologic variations ranging from syenite to diorite. Quartz diorite and granodiorite predominate. Aphanitic or porphyritic equivalents of the coarser grained rocks are present in subordinate quantity.

Two principal rock types appearing to have a direct genetic relation with high-sulfide zones are biotite-quartz diorite replacement breccias and a syenite-quartz monzonite-granite complex. The biotite-quartz diorite differs, both texturally and compositionally, from the main-phase equigranular quartz diorite. Predominant features include a felty groundmass of secondary biotite and minor K-feldspar, plagioclase phenocrysts and megacrysts, and small quartz diorite fragments. These rocks are thought to be products of deuteric alteration within breccia zones. The syenite-quartz monzonite-granite rocks occur both as matrix material within breccia blocks and in possibly larger, more homogeneous masses at depth. Texturally, they are similar to the biotitic rocks except for the presence of K-feldspar instead of biotite as the principal potassium silicate mineral.

Following the period of potassium activity, porphyritic andesites and aplites were emplaced. These rocks occur principally in areas that were subjected to intense structural deformation. Several periods of dike activity have occurred, both before and after mineralization.

Alteration affecting the plutonic rocks within the mineralized zone is of three principal types: (1) biotitic and (or) K-feldspar, (2) quartz-sericite, and (3) propylitic. Of these, the biotite-K-feldspar and quartz-sericite type are associated with copper and molybdenum mineralization, whereas the propylitic type occurs primarily in the barren pyritic rocks.

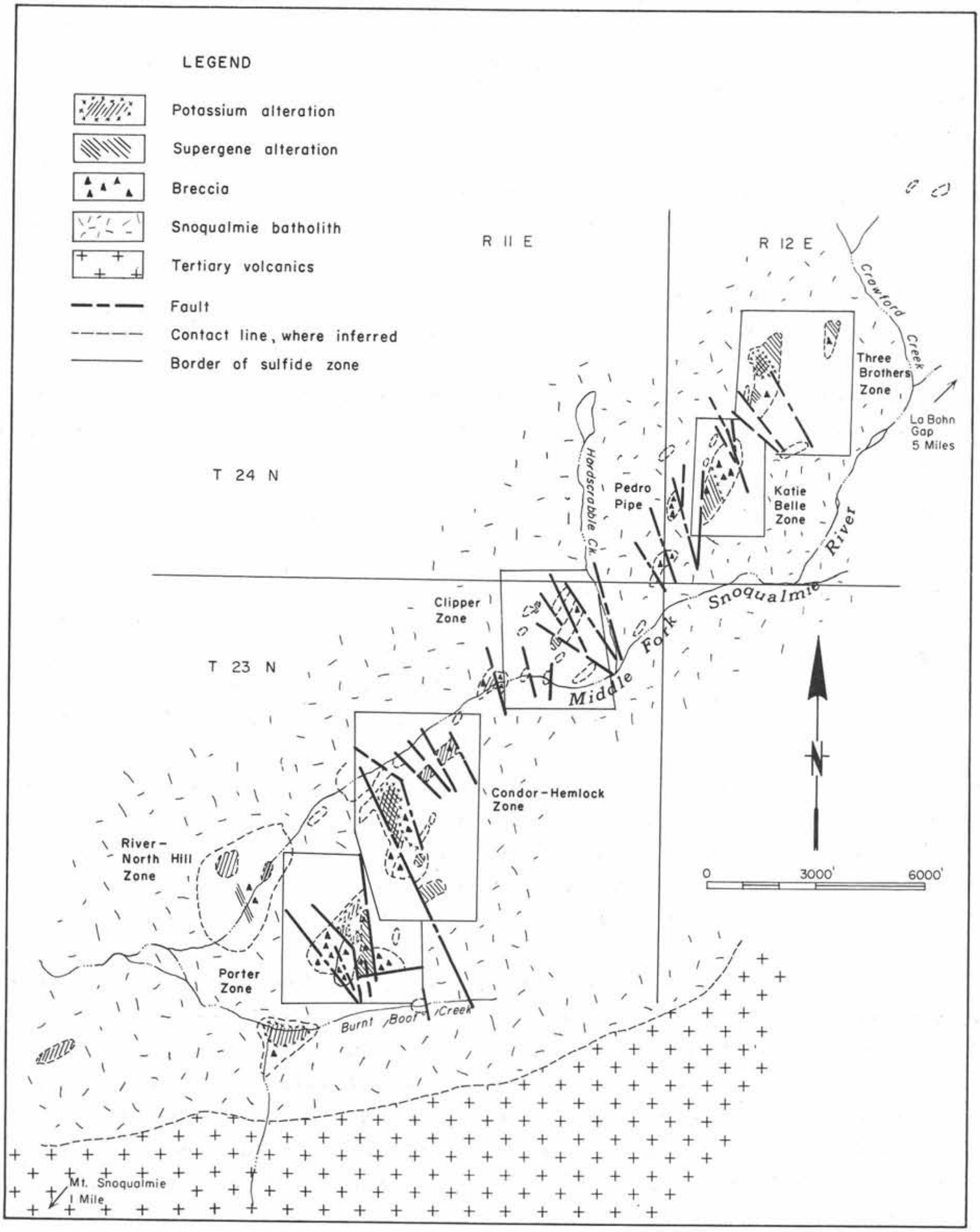

FIGURE 28.—Areal distribution of the principal sulfide zones at the Middle Fork of the Snoqualmie River property, King County, Wash.

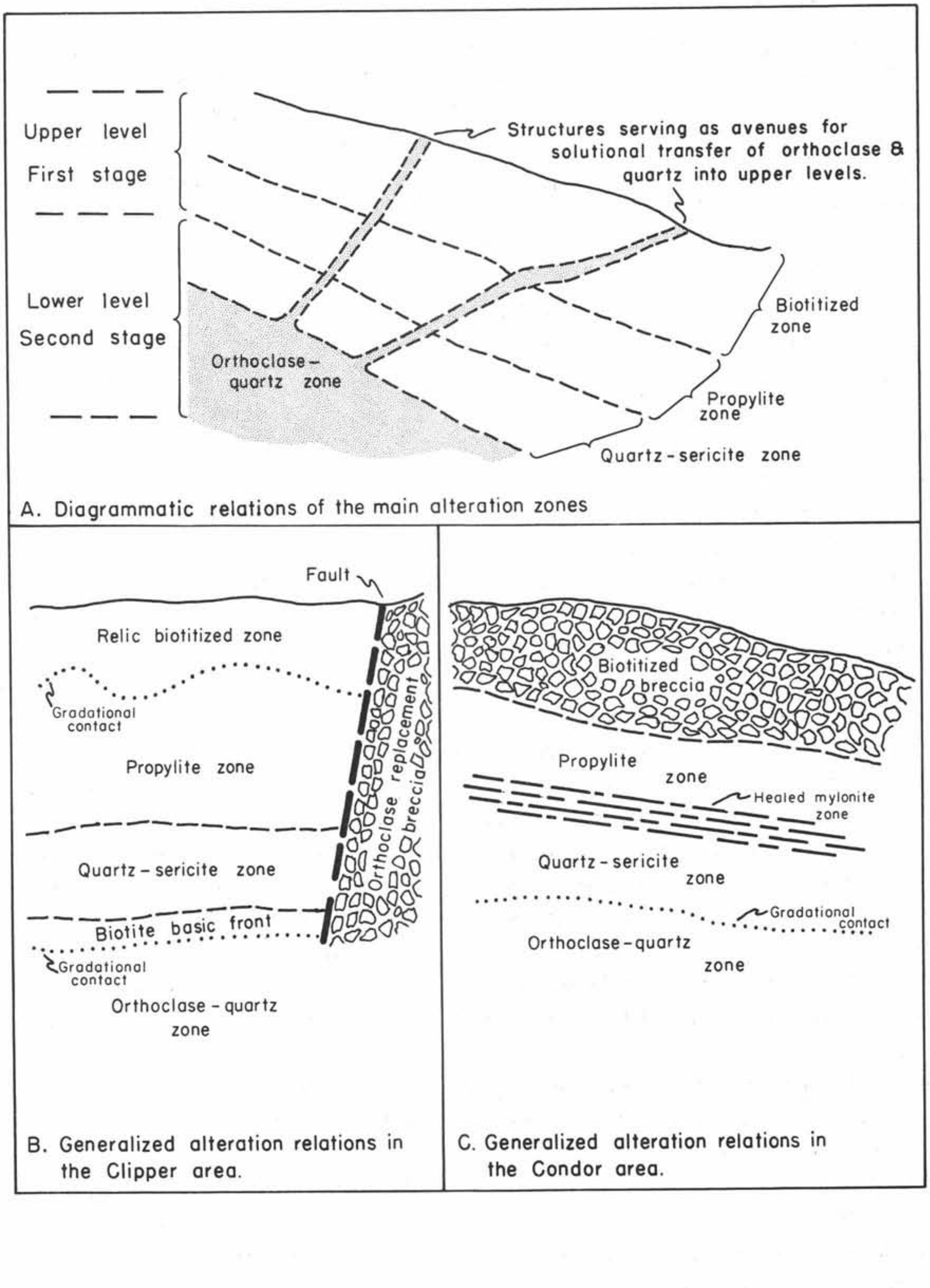

FIGURE 29.—Spatial distribution of the various alteration profiles in the Middle Fork of the Snoqualmie River area, King County, Wash.

Argillic alteration does not appear to be of particular significance except within late shears. (Chemical data on the Snoqualmie quartz diorite and its altered equivalents are shown in Table 3, on page 55.)

Evidence now available suggests the presence of a two-stage alteration cycle. It is believed that the occurrence there of either secondary biotite or K-feldspar was primarily a function of the availability of reactive constituents (aluminum and silica vs. ferrous iron and magnesium) in the parent rocks. Potassium introduced into the system reacted either with ferrous iron and magnesium to form biotite or with aluminum and silica to form K-feldspar, depending on the original chemical composition of the invaded rock. Evidence acquired by drilling indicates that the secondary biotite was formed during an early phase of potassium metasomatism at a high level, followed later by a second potassium alteration cycle in which potassium feldspar was produced at depth. The upper zone of biotitic alteration is separated from the lower K-feldspar zone by an area of propylitic and intense quartz-sericite alteration. The higher grade copper mineralization appears to be associated with the potassium silicate and quartz-sericite zones (Fig. 29).

K-feldspar commonly occurs in the upper biotitized rocks in areas where structures have served as avenues to allow solutional transfer from depth. In scattered areas, K-feldspar predominates as the principal alteration product within cross-cutting structures, although the rocks bounding the structures are biotitized and (or) propylitized. Locally, K-feldspar forms in the replacement matrix in breccia blocks near the hanging wall of the main north-northeast-trending structure. In several areas, a considerable amount of chalcopyrite is associated with these occurrences.

In at least one instance, a mafic-rich zone borders the replacement K-feldspar rocks (Fig. 29B). It is hypothesized that the mafic zone, consisting principally of biotite, was formed in a high-potassium environment from reaction with ferrous iron and magnesium migrating from the replacement zone. Petrographic evidence indicates that the granites and quartz monzonites were derived from original quartz diorites through potassium metasomatism. Relics of quartz diorite affinity are commonly present in the quartz monzonite rocks. Of these, the most suggestive are corroded high-anorthite plagioclase cores similar to those found in unaltered quartz diorite. In scattered occurrences, small remnants of quartz dioritic rock, embayed and partially replaced by orthoclase and quartz, have been noted. Ferrous iron and magnesium are virtually absent in the replacement rocks, and thus in the replacement process this original material must have been removed, probably migrating to the borders of the granite zone, where it reacted with other constituents to form secondary biotite.

The contact of the lower level potassium alteration zone with the upper level environments is either gradational or tectonic. In the Clipper area (Fig. 29B), K-feldspar and quartz were introduced into the biotitic rocks after an earlier stage of intense sericitization and chloritization. In thin section, these relations are well illustrated. The pre-existing plagioclase and mafic minerals are almost totally obliterated by sericite-chlorite alteration. Unaltered orthoclase has replaced much of the sericitized plagioclase. Late, unstrained quartz replaced both earlier strained quartz and, locally, altered plagioclase. In other areas, such as the Condor, the boundary between the K-feldspar and upper level zones appears to be tectonic (Fig. 29C). Here the propylitized rocks were mylonitized and later partially healed by K-felspar and quartz.

A general summary of the probable intrusive and alteration events leading to the present silicate distribution is presented below:

1. Emplacement of the Snoqualmie main-phase quartz diorite-granodiorite.
2. Fracturing of the peripheral shell of solidified quartz diorite. The core of the batholithic mass was still in at least a partly melted state.
3. Introduction of predominantly potassium and silica into the fractured periphery, causing extensive biotitization and silicification.
4. Superimposed chloritization and sericitization of the upper level altered rocks.
5. Continued downward solidification of quartz diorite, becoming slightly more acidic due to fractional crystallization of the residual magma.
6. Extensive shearing and fracturing.

7. Alteration of the lower level intrusive rocks. The predominant alteration silicate assemblage is orthoclase and quartz. Localized quartz-orthoclase invaded the upper biotite-propylitic zones along structures facilitating solutional transfer.
8. Late superimposed subordinate hydrothermal alteration in all zones.

The Middle Fork mineralized zone trends north-northeast from Burnt Boot Creek to Crawford Creek, a distance of more than 6 miles. This zone is characterized by a series of en echelon shears, breccia pipes, and shatter zones. Its width varies from 400 to 2,500 feet. All the principal areas of mineralization occur within this structural belt with the exception of the River-North Hill zone, which lies 1,500 feet west of the main structure (Fig. 28).

It is probable that the original north-northeast-trending structure was once a continuous zone. However, a complex series of north- to northwest-trending cross faults have cut the original structure, thus creating a series of truncated blocks. The largest measurable vertical displacement on a northwest cross fault is about 700 feet, but structural indications in the Porter area suggest minimum displacement of 1,000 feet.

Several breccia pipes, occurring along the main structure zone, are characterized by: (1) rotation of fragments, (2) rounding or sub-rounding of fragments, (3) fragments of variable lithologies, (4) tendency toward ellipsoidal geometry of the pipe, (5) steep contacts, and (6) sulfide zonation and complex sulfosalt occurrences. The structural control for at least one pipe appears to be an intersection of a northwest-trending fault with north-northeast-trending shears. Others appear to be more elongate zones parallel to the main north-northeast structure.

The wide variety of sulfide deposits in the Middle Fork area reflects the complexity of the total environment. Chalcopyrite and molydbenite predominate as the economically significant sulfides, whereas pyrite and (or) pyrrhotite are the main gangue. The sulfides occur as: (1) disseminations in biotitic matrix in replacement breccias, (2) disseminations in K-feldspar-quartz-rich matrix material in replacement breccias, (3) disseminations in K-feldspar-rich rocks in intrusive plugs, (4) open-space fillings in breccia pipe vugs, (5) high-grade veins in isolated structures, (6) ubiquitous fracture fillings, and (7) small pods and minor disseminations in quartz-rich breccia zones. The total sulfide content appears to be a direct function of the intensity of deformation and the chemical nature of the subsequent alteration.

At least two stages of copper mineralization have occurred. The earliest appears related to the initial stage of deuteric and hydrothermal alteration affecting the upper level rocks. The second and seemingly more economically significant stage of copper mineralization appears related to the later, deeper seated potassic alteration cycle. During the later stage, steeply dipping cross faults ranging in strike from N. 10° E. to N. 30° W. in the Porter-Hemlock-Condor zone appear to have been loci for sulfide deposition. In many instances, sulfide mineralization is most extensive in tensional fractures related to the cross fault systems. Multi-cyclic structural activity along the cross fault systems is evidenced chronologically by: (1) early shearing, (2) andesite or aplite dike emplacement along the shear zones, (3) shearing in the dike rocks, and (4) sulfide deposition along the later shears in the dike rocks. Molybdenite mineralization appears to be principally related to late silica introduction along new fracture sets, possibly postdating the later period of copper deposition.

A crude pattern of base metal zoning exists in the Middle Fork area. To the northwest in the Miller River area and to the northeast in the LaBohn Gap area, lead and zinc mineralization occur. To the southwest, on the north slope of Mount Snoqualmie, zinc, present in marmatite in breccia zones, is relatively common. Lead and lesser amounts of zinc are found southeast of the Middle Fork, in the Gold Creek area. In the Middle Fork area proper, lead and (or) zinc are absent except in rare breccia pipe or isolated vein occurrences.

In summary, the physical and chemical environments in the Middle Fork area present a favorable combination for sulfide deposition. As elsewhere in the Cascades, Tertiary intrusive activity, acidic magmatic differentiation, transverse structural systems, and, in some instances, a structural couple pattern are major controlling factors in the distribution and concentration of sulfides. In the Middle Fork area all these conditions are present, and the end product is attested by the wide variety of sulfide occurrences over an area of several square miles.

Western Kittitas County

The sulfide occurrences in western Kittitas County (Fig. 30) discussed here are northeast of Snoqualmie Pass and southeast of the Middle Fork of the Snoqualmie area, in the Gold Creek and Mineral Creek drainages. These zones,

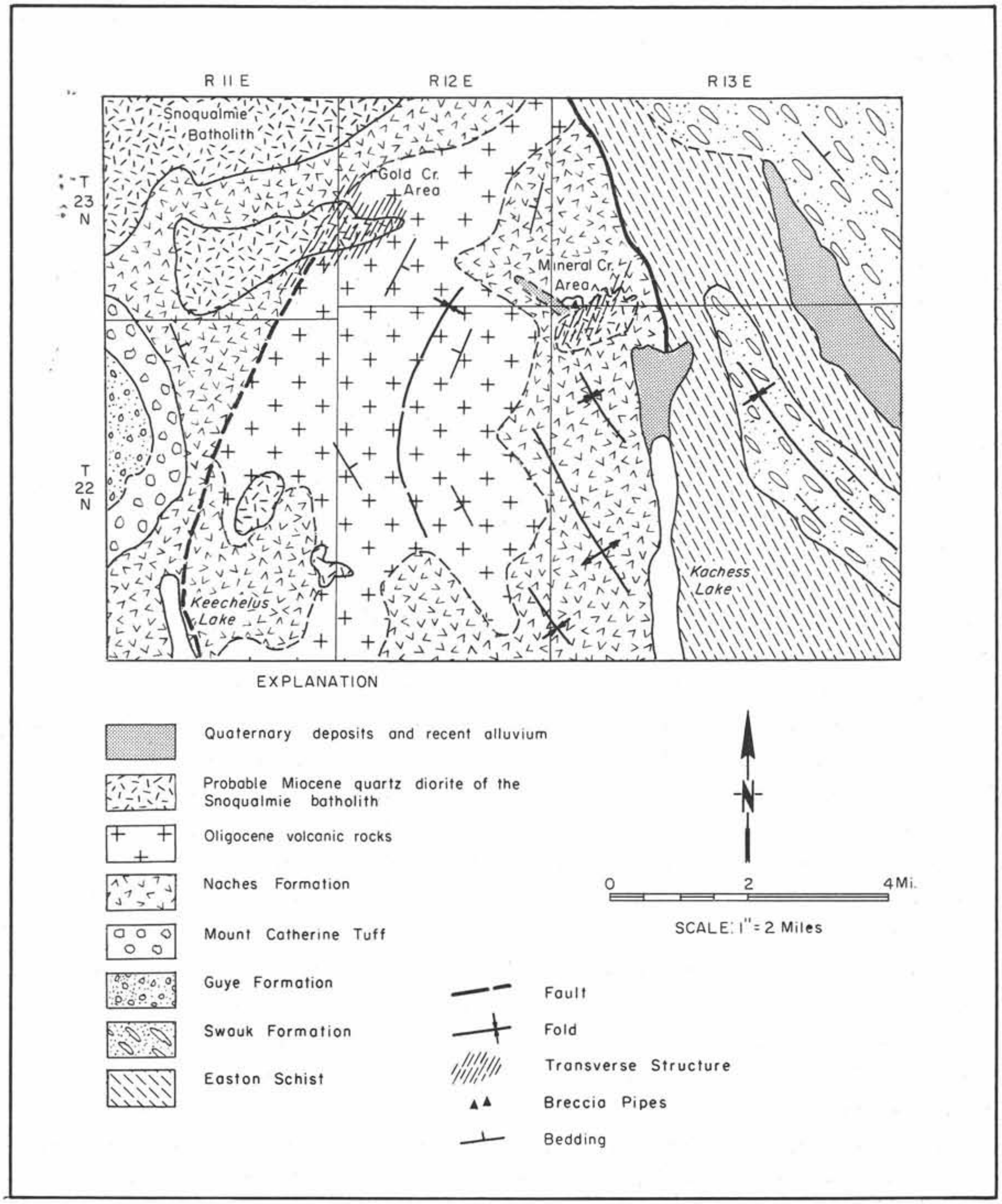

FIGURE 30.—Generalized geologic map of western Kittitas County in the Gold Creek and Mineral Creek areas.

although not yet studied in detail, appear to be similar in overall aspect to the Middle Fork environment. In particular, these gross similarities include:

(1) a subparallel set of northeast-striking transverse structures;

(2) spatial relations of propylitic, quartz-sericite, and biotite-orthoclase alteration;

(3) related intrusive host rocks; and

(4) possible synchronous sulfide deposition cycles.

The principal difference between the two districts is in the exposed levels of alteration and mineralization. It is presumed that in the Middle Fork Snoqualmie area about 1,500 feet of the top part of the batholith has been removed by erosion. This presumption is corroborated by the higher temperature alteration environments. In the Gold Creek-Mineral Creek areas the exposed mineralization occurs in the uppermost levels of the plutonic rocks, along the contact with the overlying volcanics. Wall rock alteration is mostly of the propylitic type, and pyrite is the predominant sulfide. Only with deep drilling have significant changes in this alteration-sulfide pattern become apparent. The propylitic alteration changes to quartz-sericite and (or) biotite-orthoclase pyrrhotite occurs in lieu of pyrite. Chalcopyrite content increases proportionately in the pyrrhotite zones.

The Gold Creek area exhibits a number of complex geologic environments in detail, but the overall geologic picture is relatively simple. A heterogeneous series of volcanic rocks, Eocene to Oligocene in age, have been intruded by a satellitic stock of the Snoqualmie batholith. The volcanic rocks in the contact aureole have been extensively hornfelsed and pyritized. Most hornfelsing has occurred in hornblende or low-grade hornfels facies. The contact pyritization in the volcanic rocks is responsible for the formation of the numerous pyrite gossans visible in the Gold Creek area. Characteristically, goethite is the common limonite in these gossan occurrences. Locally, the volcanic rocks in the contact zone have been brecciated and silicified. Intrusive breccias are rare.

The satellitic stock of the Snoqualmie batholith crops out mostly at the lower elevations in the Gold Creek valley. The intrusive rocks range in composition from diorite to granodiorite, the predominating rock being quartz diorite. Although there is no exposed connection of this stock with the main batholith to the northwest, the overlying volcanic rocks forming the high ridges at the head of Gold Creek show evidence of intense hornfelsing from an underlying intrusive mass. Two miles north of Gold Creek, in the Burnt Boot Creek area (south end of the Middle Fork zone), the contact of the main Snoqualmie batholith dips gently south at the 3,000-foot level. In Gold Creek the batholithic rocks crop out at about the 3,500-foot elevation. This pattern suggests a slight rise of the batholith roof in the Gold Creek area.

The quartz diorite exposed in the Gold Creek drainage has been pervasively propylitized. With depth, however, as noted in drill cores, potassium alteration increases. The change between alteration types is gradational. Most of the primary biotite and hornblende have been replaced by felty masses of secondary biotite. Locally, leucocratic replacement zones and small dikelets of K-feldspar material occur. Superimposed over much of the potash alteration is late chlorite-sericite alteration. This type commonly is present as a halo around the biotite and K-feldspar zone.

Structures in the Gold Creek area have not been systematically studied, but strong northwest shearing appears to be present. A complementary set of northeast-trending structures was noted in the creek canyon walls. These northeast structures, occurring as en echelon shears and sheet joints, are the most predominant structure set in the zones of high sulfides. Away from the sulfide zones, they become subordinate to northwest-trending structures. Several northwest-trending folds have been mapped in the volcanic rocks. The period of deformation causing the folding predates the emplacement of the quartz diorite.

Sulfide mineralization in the Gold Creek area is widespread. In the overlying volcanic rocks, pyrite is almost the exclusive sulfide; rarely is chalcopyrite present. Sulfide mineralogy in the intrusive is more complex. Pyrite again predominates, but pyrrhotite appears to occur in lieu of pyrite at depth. Chalcopyrite tends more to occur with pyrrhotite. Both chalcopyrite and pyrrhotite tend to occur in the potassium alteration zones.

The geology of the Mineral Creek area is more complex that that of Gold Creek. The oldest rocks, occurring east of the main mineralized zone, consist of pre-Tertiary greenschists, phyllites, and greenstones. West of the imbricate schist belt, continental rocks of the Swauk Formation crop out. The Swauk rocks appear to be unconformably overlain by Eocene to Oligocene volcanic flows and breccias. The oldest of these volcanic rocks is a rhyolite tuff unit that is overlain by andesitic flows and rare intercalated sediments.

These rocks were intruded by a quartz diorite mass, the Mineral Creek stock. Although direct evidence is lacking, this stock also is thought to be a satellite of the Snoqualmie batholith, the bulk of which lies west to northwest of the Mineral Creek area. The extensive hornfelsing in the overlying volcanic section indicates that the entire area could be underlain by Snoqualmie intrusive material.

The quartz diorite is intruded by several small, irregular-shaped masses and dikes of dacite porphyry. Several dikelike masses of intrusive breccia also occur in the quartz diorite.

All pre-intrusive rocks have been steeply folded along approximately north-south axes. Major northwest-trending faults cut all rocks of the area. An en echelon northeast-trending sheeting system parallels the creek valley, passing through most of the more significant sulfide occurrences.

Numerous breccia zones, including several pipelike masses, occur in the contact aureole between the intrusive body and the overlying volcanic rocks. Commonly, these pipes are loci for sulfide deposition. The largest pipe, situated at creek level along the east contact of the stock, was the scene of fairly extensive exploration in the 1920's (Patty, 1921). Here the sulfides, consisting predominantly of pyrite and chalcopyrite in a ratio of approximately 1:1, occur as disseminations in both the matrix and fragments of the breccia and in crosscutting, stockwork-type veinlets. Pyrrhotite occurs in lesser amounts. Molybdenite was noted at a few scattered localities. Chalcocite and covellite are commonly noted in the near-surface supergene zone. The maximum depth of leaching appears to be less than 10 feet.

The breccia is characterized by biotitized fragments of quartz diorite in a predominantly quartz matrix. Locally, K-feldspar has been introduced into both the fragments and matrix. On the intrusive side of the breccia contact, the quartz diorite has been biotitized and silicified.

The main breccia zone is exposed over a distance of 140 feet in an east-west direction along Mineral Creek. North and south of the creek, extensive cover prevents investigation. Farther up the hill on both sides of the main outcrop zone, hornfelsed pyritized volcanic rocks are found, suggesting that the intrusive and possible breccia zones occur at a subjacent level.

Silver Star Stock — Skamania County

The Silver Star area (Fig. 30) is in the southern Washington Cascades about 10 miles north of the Columbia River. The topography is relatively gentle; consequently, brush and overburden are abundant and outcrops are rare.

The oldest known rocks in the area consist of weakly folded late Eocene to Miocene volcanic rocks, composed predominantly of andesitic flows, tuffs, and breccias. These rocks were intruded by the Silver Star stock, of probably late Miocene age. Felts (1939) mapped the stock and found that the central part of the intrusion, which is predominantly granodiorite compositionally grades into subordinate quartz diorite along the periphery of the mass.

Few structural data are available for this section of the Cascades. In general, the northwest patterns still persists marked mainly by open fold axes in the volcanic rocks. Of particular interest, however, is Heath's (1966) tabulation of strikes of the principal veins and shears at the various prospects located in or adjacent to the stock. He noted that most of the mineralized structures trend in a general east-west direction, roughly normal to the north-south elongation of the stock. In a similar instance at Helena Peak, north of the Sultan Basin-Silver Creek area, these transverse structures created tensional openings that later became channelways for ascending mineralizing solutions.

Numerous lode prospects have been located in the Silver Star area, but only a few appear to be of possible economic significance. However, the several breccia occurrences near the northern edge of the stock indicate some potential for base metal production.

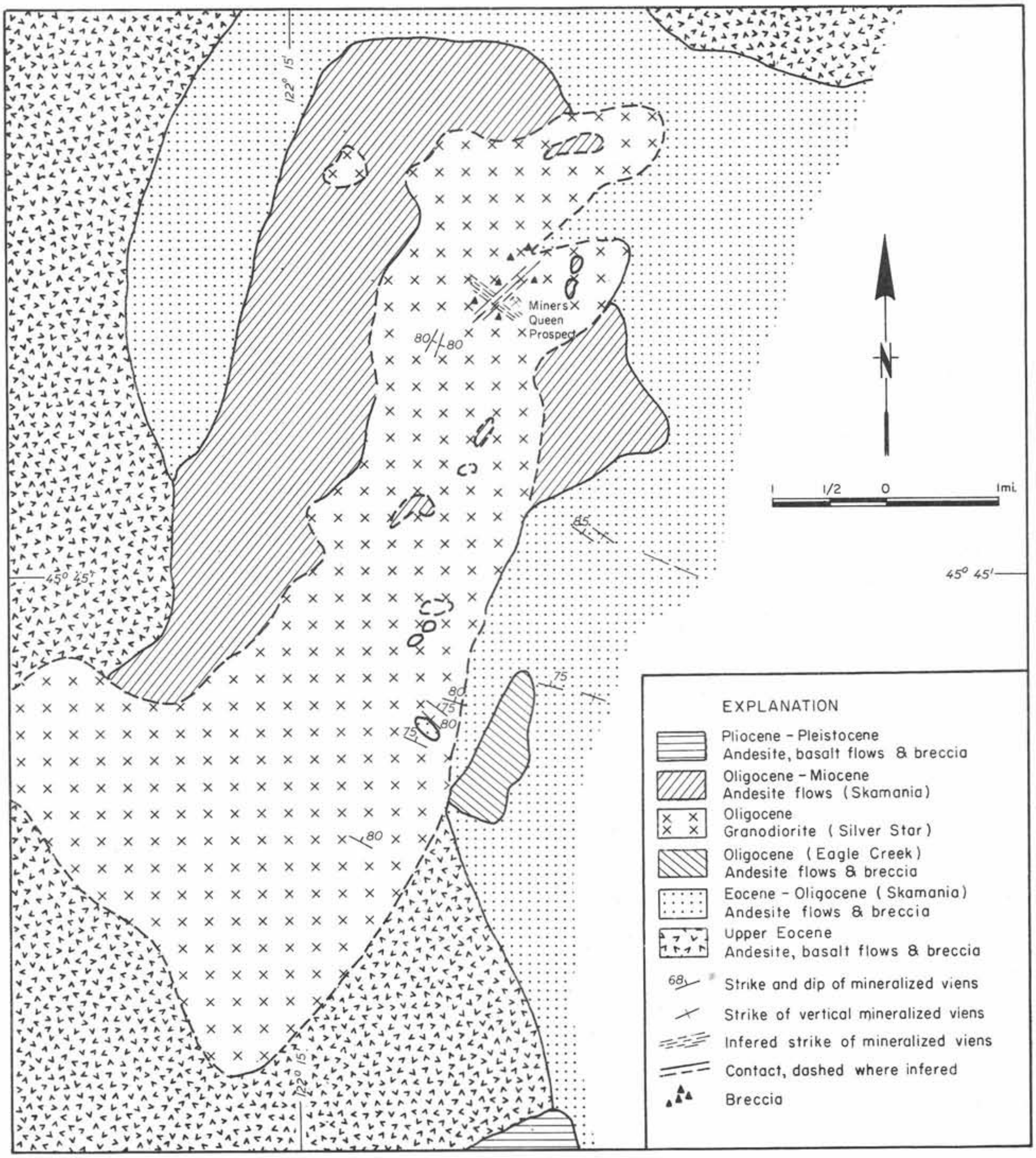

FIGURE 31. — Geology of the Silver Star area, Clark and Skamania Counties, Wash.

Of the known breccia zones, the largest is in the Copper Creek area, at the Miners Queen prospect, where the breccia is confined to the intrusive rocks along a general northeast-trending zone. The breccias are discontinuous, having been cut by a complex series of post-mineral faults.

Intense wall rock alteration is present in the brecciated zones. In general, the intensity of alteration and subsequent sulfide deposition appear to be a direct function of the degree of brecciation. Adjacent country rock, even a few feet away from the breccias, is little altered and, at best, sparsely mineralized.

Alteration of the granodiorite has been mainly of the secondary biotite-orthoclase type. Silicification is ubiquitous in the brecciated rocks. Texturally, the altered rocks are porphyritic as opposed to the equigranular nature of the unaltered intrusive rocks. The alteration silicate mineral assemblage of quartz-sodic andesine-orthoclase-biotite characterizes these rocks. Quartz is partially introduced. The plagioclase has been partly decalcified from calcic andesine. Much of the orthoclase is secondary, replacing plagioclase. Fine-grained felty biotite is secondary. Primary hornblende has been obliterated or pseudomorphed by biotite. Minor chloritization of mafics and sericitization of feldspars is superposed over the earlier alteration types.

Oxide calculations based upon several modes of K-feldspar-altered granodiorite are given in Table 11.

TABLE 11.—Summary of weight percent of major oxides (calculated from modes) in the K-feldspar-altered rocks of the Silver Star stock, Miners Queen prospect 1/

Oxide	Percentage	Estimated percentage point increase or decrease
SiO_2	71.3	+7
Al_2O_3	16.1	±same
Fe_2O_3	----	-0.4
FeO	0.9	-3.8
MgO	1.2	±same
CaO	2.6	-2.4
Na_2O	2.9	+0.3
K_2O	4.1	+1.3
H_2O	0.68	±same

1/ In this table, the approximate increase or decrease of major oxides is based upon a general modal average for intrusive rocks comparable to the general compositional types in the Silver Star stock. Contained sulfides are not included in the calculations.

Outward from the more intensely K-feldspathized-biotitized rocks, quartz-sericite and propylitic alteration is confined to narrow reaction zones.

Mineralization within the breccia zones occurs in the matrix and as disseminations in the fragments. Chalcopyrite, magnetite, pyrite, pyrrhotite, and molybdenite occur in decreasing order of abundance. Heath (1966) noted that chalcopyrite and pyrite were contemporaneous, commonly replacing earlier magnetite. Molybdenite is late, probably associated with a late stage of quartz introduction. Matrix gangue includes quartz, tourmaline (var. schorlite), and orthoclase.

The breccia zones in which these deposits occur are strikingly aligned in a northeast direction. Present data indicate that the individual mineralized breccia occurrences are relatively small. The large amount of overburden, however, severely restricts observations. Considering the favorable structural and chemical environments of these breccias, a substantial potential seems reasonable.

APPENDIX I

EXPLORATION TECHNIQUES WITH SPECIAL EMPHASIS ON CASCADE PROBLEMS

The accumulation of raw physical data is imperative in the appraisal of any area, but such information must be placed in its proper perspective and used cautiously. In recent years, many companies and geologists have relied heavily on certain facets of exploration such as geochemistry and geophysics. Admittedly, these tools are of great value to the geologist in his search for ore deposits, but the data acquired from such work must be integrated into the total exploration picture. Taken at face value, much of the geophysical and geochemical data can be misleading and wasteful of time, money, and effort in areas of low potential. Geochemical and geophysical data must be combined within the known geological framework. Park (1964), in his paper "Is Geologic Field Work Obsolete?", emphasized that mineral exploration is fundamentally a function of structural geology and petrology and that mineral deposition is inseparably tied to such phenomena as orogenic history and the emplacement of composite batholiths. He further stated that exploration for concealed mineral deposits will remain handicapped until such problems as orogenic cycles, batholithic emplacement, and intrusive chemistry are better understood.

As previously stressed, an ore deposit represents an anomalous concentration of material in its natural state. In searching for these conditions, the geologist must differentiate and recognize varied anomalous facets, whether geological, geochemical, or geophysical. Only in this way can he be relatively sure that he is proceeding in the most efficient and economical manner. Finally, in evaluating a property, be it a raw prospect or an operating mine, the exploration geologist's primary concern is to determine potential profits. In order to accomplish this, he must acquire certain basic data, interpret these data in their proper perspective, and reach a decision to pass on to the management.

Regional Studies

Background geologic data on the Cascades is voluminous, yet of varied reliability. Nevertheless, the geologist should avail himself of this information before initiating work. Eventually, with experience, he will be able to evaluate this literature. Among the best sources of data are the unpublished theses in the science library of the University of Washington, in Seattle, and at the office of the Washington State Division of Mines and Geology, Olympia. The geologist undertaking to study these materials should himself have a background in igneous and metamorphic petrology and structures. Without this, he will quickly be lost in the maze of petrologic and structural descriptions.

Jerome (1959) presented an excellent synopsis of the various procedural steps to be followed in the exploration of target areas within the continental framework. On a reduced scale, the whole of the Washington Cascades is a potential target. A guideline that might be followed during the initial phase of indirect appraisal follows. Procedures of direct appraisal in the field are discussed later.

Regional map analysis.—The various geologic criteria appearing to have an important bearing on sulfide deposition have been described. The Geologic Map of Washington at a scale of 1:500,000 (Huntting and others, 1961) shows many of the data, although more recent data have modified the picture since the map was published. Smaller scale geologic maps (e.g., Misch, 1966) are of great help. If regional studies of the range are part of a long-range major program, a series of geologic maps to serve as overlays on a suitable base map should be compiled. Although time consuming, the end product not only would constitute a useful series of reference maps that could be modified in the field but would provide an effective method of acquainting the geologist with the regional distribution of rock units and structural trends.

Other maps could be prepared to suit the particular needs of the project; for example, metal commodity maps (separate map for each metal) showing the distribution of the various reported occurrences of metals in the range. An excellent reference is "Inventory of Washington Minerals, Part II, Metallic Minerals," (Huntting, 1956). Some of the data in this voluminous work are of questionable reliability because they were taken from descriptions by property owners and (or) prospectors. Even so, it is still the best reference available for the reported distribution of metallic minerals within the range.

If so desired, separate maps incorporating such information as the tectonic patterns, geochemical information, and perhaps land status and property locations could be compiled by the exploration team. If such maps are to be prepared, they should be designed so that new information can be easily added as it is gathered.

Geologic studies. — In order to become directly acquainted with the rock units and alteration types characteristic of the Cascade provinces, the geologist may desire to spend some time examining, both in hand specimen and in thin section, various suites of rocks collected from the range. The Geology Department of the University of Washington requires that each student, upon completing a Cascade petrology thesis, deposit a representative suite of rock samples and thin sections in the department. These suites are available for public inspection. In conjunction with this report, an extensive suite of rocks and thin sections has been prepared to illustrate the various types of wall rock alteration associated with Cascade sulfide deposits, and is available for inspection at the office of the Washington Division of Mines and Geology, in Olympia.

Property reports. — There is a variety of company and government reports on file, particularly at the office of the Division of Mines and Geology. Although some are reliable, many are not. Recent work by State geologists in revising property information and geologic data on the mineral occurrences in various Washington counties will be of considerable aid.

These methods of indirect appraisal are of incalculable value when planning and (or) designing exploration operations in the Cascades. Obviously, the geologist must decide how far he wishes to proceed in literature evaluation and map compilation. In any event, it is imperative to establish the necessary background knowledge of regional and local environments.

Mapping and Sampling Procedures

Following the indirect appraisal period as outlined above, assuming the geologist has both delineated a target or series of targets, and, if required, has made the necessary option or land acquisition arrangements, he is ready to begin direct appraisal methods in the field. These primarily include geologic mapping and representative sampling of surface materials.

Geologic mapping can be accomplished on many scales; however, initial mapping on a scale of 1:400 or larger is recommended. This enables the geologist to study the background environments surrounding the potential anomalous zone. Particular attention must be paid to such features as structure, intrusive relations and phases, intrusive contact phenomena (if present), and wall rock alteration. Structure mapping should include all observations at a given station, including such information as joint attitudes, measurable displacements (especially where these data can aid in establishing the sequence of deformational events), microfaults, and larger shears or faults. Many of these data turn out to be meaningless. Conversely, many are used to establish valid and helpful structural patterns. For example, it was shown earlier (on page 43) that the evaluation of hundreds of joint measurements in the southern part of the Cloudy Pass batholith revealed two predominant preferred stress orientation directions vital in the structural setting of the Miners Ridge copper deposits.

Once the regional picture has been established, more detailed mapping in the selected areas of interest is then designed to fit the requirements of the problem. Here, considerable attention must be paid to the orientation of the mineralized structures, sulfide occurrences, their type and distribution, and wall rock alteration. A representative suite of rocks, with particular emphasis on the various alteration types encountered, should be collected, thin sectioned, and petrographically studied as soon as possible after initiating a major exploration venture. This procedure will facilitate mapping of alterations and should be particularly useful on possible long-term projects. The thin section data, corroborated with hand specimen analysis, should enable the geologist to more easily recognize and map alteration types and intensities in the field. On some projects, it may be of value to petrographically map and contour alteration intensities. Figure 32 shows the intensity contours of chloritization and sericitization in and adjacent to a copper deposit in the North Cascades. The alteration highs correlate well with the delineated boundaries of the main ore deposits, one of which is not exposed at the surface. The alteration contours also show a striking alignment to the northeast, paralleling the main northeast-trending transverse structural belt. This particular attempt to correlate alteration intensities with sulfide occurrences and controlling structures proved highly satisfactory. However, if methods such as contouring alteration intensities are attempted, greater accuracy and thus reliability can be obtained by grid-sampling the area of interest.

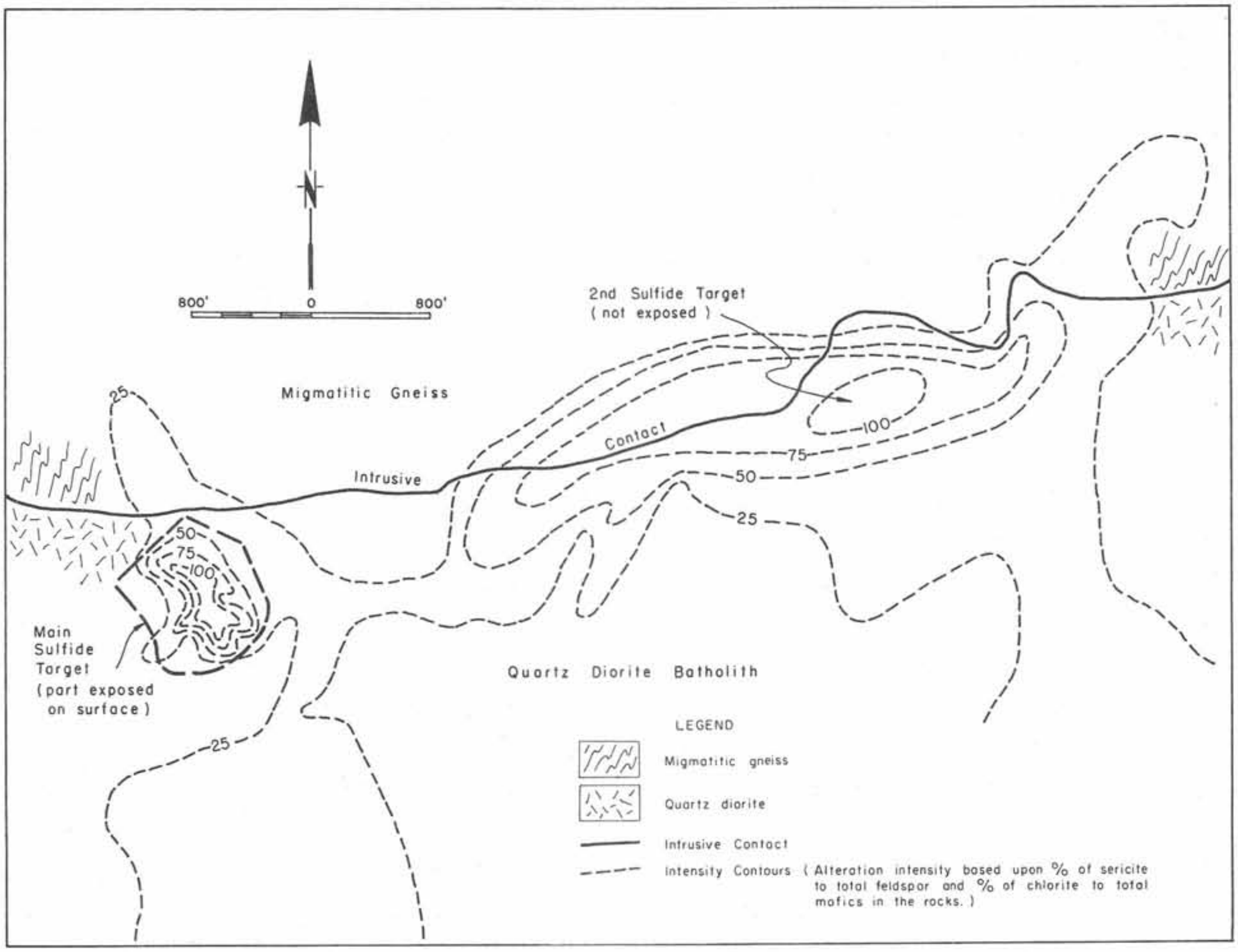

FIGURE 32.—Use of alteration (chloritization and sericitization combined) intensity contours to delineate principal sulfide targets. Example based upon results of an actual alteration study at a copper prospect in the North Cascades.

Particular care must be taken in the sampling of surface material to insure that the sample is truly representative. For example, many copper deposits in the Cascades have been subjected to very shallow supergene alteration. If a sample trench is blasted through the supergene zone into the hypogene sulfide zone, the sampler should diligently exclude all supergene material from his sample. Commonly, at the base of the supergene layer, a thin zone containing secondary chalcocite, covellite, bornite, cuprite, or even native copper may occur. These zones have not developed to an economically important thickness, but the contamination of a protore sample with some of this enriched material could significantly affect the accuracy of the sampling program.

Most sampling should be done, where possible, on a grid system. Studies have shown that the most reliable sample consists of a series of small chips relatively uniform in size, taken over an area of about 25 square feet and weighing a total of 1 to 2 pounds. In many instances, this is impossible and the sampler must establish his own requirements. The important thing is that he remain constant in his procedure.

Geochemical Prospecting

The application of geochemical prospecting can greatly aid the exploration geologist if the data gained from such an appraisal are placed in their proper perspective. It has been emphasized (p. 91) that in base metal exploration, the geologist is concerned with establishing anomalies within the regional framework. These anomalies are initially established through reconnaissance surveys and localized by detailed surveys. Hawkes and Webb (1962) pointed out that the interpretation of geochemical prospecting data, in terms of possible mineral deposits, is fundamentally a geologic rather than a chemical problem. This is certainly applicable in the Cascades. The geochemical data must be integrated into the known geologic picture before meaningful interpretation is attempted. As a case in point, stream sediment analyses in the Silver Creek drainage (east of Index, in Snohomish County) indicated the existence of a widespread, strong copper anomaly. Detailed geologic mapping in the creek drainage revealed a series of discrete, isolated chalcopyrite veinlets of no apparent economic significance paralleling the creek. These copper occurrences were restricted principally to the valley floor. Taken at face value, the geochemical data could have been interpreted as evidence of an extensive anomaly of possible major importance.

Stream Sampling

Stream samples of either sediment or water can be collected on various spacings, depending on whether regional reconnaissance or detailed surveys are intended. This procedure constitutes a relatively cheap exploration tool, particularly in areas where few geologic or prospecting data are available.

When sampling water, considerable care must be exercised in recognizing the physical characteristics of the stream. These characteristics are highly variable, depending, for example, on the time of year. In the Cascades, the normal high-water seasons come in late spring, during annual runoff of the winter snowpack, and in late fall as a result of heavy rains. The increased discharge and capacity of the streams during these periods significantly dilute (from the standpoint of possible metal content) the water sample. Seasonal changes in stream pH and bulk composition of the water also affect the sample. For these and other reasons, the widespread use of water sampling as a method of geochemical prospecting in the Cascades is not recommended.

With proper care, stream sediment sampling can be of considerable aid in an exploration venture, particularly in those areas where little background information is available. Comparative studies in the Cascades by several mining companies have shed light on many of the problems concerning the selection of sample material and the interpretation of results. These findings are briefly given below. It must be emphasized that because of the preponderance of copper and molybdenum mineralization in the range, these data are applicable mostly to copper and molybdenum anomalies. Heavy metal values in an area such as the Cascades appear to be of little significance.

Selection of sampling material.—Studies designed to help determine the best sampling material have shown that the copper content of the silt trapped under live moss growing on rocks in the streambed is generally higher than that in the normal silty fractions in the stream channel. Furthermore, in sampling channel silt, the finer size fractions commonly carry a higher copper content than the coarser fractions. Below -48 mesh, however, variations in sizing are of little significance.

Exchangeable vs. total copper values.—When prospecting for copper anomalies, the geologist may choose to analyze the sample by using a simple field test for exchangeable copper; e.g., the dithizone tests described by Hawkes (1963), or by running the sample for totals. All geochemical samples collected in the Cascade province should be submitted for totals, particularly on copper. The reason for this is simple. In many areas, primary copper sulfides are exposed at the surface. Little oxidation has occurred, thus exchangeable copper cations are rare in the downslope wash. The resultant geochemical profile in such a case might show a series of low, possibly nonanomalous copper values for the dithizone field tests but much higher, possibly strongly anomalous total copper values. Numerous copper prospects in the Cascades, particularly those in the rugged northern regions, do not register anomalous exchangeable copper values downslope but are very anomalous in total copper. The major contribution of field tests for exchangeable copper is the quick availability of some results. Final interpretation of geochemical data should always await the receipt of total values.

Interpretation of results.—Several factors must be considered in the evaluation of the geochemical data. Hawkes and Webb (1962) pointed out that a fairly dependable value for determining the threshold of a geochemical anomaly can only result from an orientation survey in an area of known geology and mineralization. This procedure is strongly recommended in the Cascade province, where geochemical prospecting is still a relatively new tool and background data must be established. To illustrate, the anomalous threshold for a stream sediment value in the Middle Fork of the Snoqualmie River area (geologically comprising batholithic rocks and altered volcanics) is 100 ppm copper. In the North Cascades (predominantly pre-Tertiary metamorphic rocks and Tertiary plutons), the threshold is 40-50 ppm copper. These backgrounds can vary rapidly. Furthermore, the size of the drainage basin must be considered when evaluating the data. Again to illustrate, a large area of pervasive copper mineralization such as on the Middle Fork of the Snoqualmie River is reflected at least 10 miles downriver from the property. There, copper values in stream sediments are still in excess of 100 ppm. The Middle Fork drainage basin, upstream from the point of the threshold anomalous value, encompasses an area of over 150 square miles. Consider, conversely, a value of 100 ppm copper from a small creek draining an area of approximately 2 square miles. Here, the copper value might reflect the occurrence of a small, economically unimportant, copper sulfide vein. It is exceedingly costly to follow up "anomalies" of this type. Proper interpretation of stream geochemical data must be correlated with all applicable topographic or geologic features recorded. Hawkes and Webb (1962, p. 287) stated that "appraisal of significant anomalies, once they have been identified, calls for a critical review of the intensity and form of the anomaly taken in context of the general favorability of the geologic environment, together with consideration of all those environmental factors that may enhance or suppress anomalous patterns." A classic example of the structural influence on the dispersion of copper values in stream sediments is shown at one of the major copper prospects in the North Cascades. There the main copper occurrences are cut by a strong series of en echelon transverse shears paralleling the east-west-trending main valley. The deposit and the transverse structural system are situated on the north slope of the valley. Much of the ground water passing through the copper area enters into the east-west-trending structures and drains west into small tributary drainages flowing south into the main creek. The small western tributaries are thus contaminated by metal from the copper deposits lying to the east along contour. The apparent geochemical dispersion pattern for copper is an alongslope string of anomalous values when, in reality, the copper occurrences in rock are restricted to the eastern end of the anomaly. Without the structural data base for interpretation, considerable time and effort could have been spent in following up an anomaly, the source of which lies laterally to the east rather than upslope.

In the Cascades, a strong anomaly may indicate the presence of (1) a large area of low-grade mineralization, (2) swarms of small high-grade deposits, or (3) large areas of weak pervasive mineralization in highly fractured rock that is susceptible to leaching action by circulating ground water. Furthermore, the absence of a strong anomaly does not necessarily mean the absence of economically important sulfide bodies. It may be only the effect of a low rate of chemical attack on the bedrock (Hawkes and Webb, 1962). Just as commonly, the absence of an anomaly may be the result of dilution or precipitation of the metal somewhere along the drainage system between the source and the sample site.

Followup of an established anomaly.—Delineating the source of an established anomaly is somewhat dependent on the physical characteristics of the terrain. In some instances, particularly where a strong anomaly exists in a major drainage, detailed sampling surveys upstream from the initial anomalous point can be made. Utilizing this approach, the sample spacing should be reduced to a scale where all significant tributaries are sampled. However, this procedure commonly causes serious access problems; major streams must be crossed and recrossed. During late spring and fall, when water courses are swollen, effective sediment sampling may be impossible. In any case, the upstream anomalous cutoff must be established. Once the anomalous spread has been delimited, more detailed sediment or soil sampling can be utilized to further define and perhaps pinpoint the anomaly.

Commonly in the Cascades, geochemical followup is prevented because of terrain limitations. Here the followup procedure must rely heavily on direct geologic examinations of bedrock. In some instances, the source of the anomaly, as defined geochemically, is concealed. If the anomaly is of sufficient strength to justify the cost, a geophysical survey, particularly one employing electrical methods, could aid in accurately defining the potential target zone.

Soil Sampling

Sampling and analysis of residual soils has long been recognized as an important exploration technique in areas of extensive cover. It can be utilized to further delimit a geochemical anomaly initially established by stream sediment surveys or to indicate extensions of mineralization where exposed sulfide occurrences disappear under cover.

Hawkes and Webb (1962) presented a summary of the processes of soil formation. Most geologists have little background in soil development; therefore, a brief discussion of the soil profile is relevant. Soils are characteristically organized into layers differing from each other and from their underlying parent material in their properties and composition. Taken together, these horizons constitute a soil profile. Soil profiles vary in their physical and chemical properties within wide limits according to their genetic and geographic environment. Most profiles comprise three principal layers, designated from the surface downward, the A, B, and C horizons. The A and B horizons constitute the "true soil," whereas the C horizon is the parent material from which the soil is derived. The entire sequence is not always present, as in a poorly developed soil lacking an A or B horizon. The A horizon is either a zone of organic incorporation (designated the A_1 horizon) or a zone of leaching (designated the A_2 horizon). Resistant primary minerals, rock material undergoing decomposition, and flocculated colloids tend to remain. The A horizon and the overlying organic layer are characterized by intense biological activity. Much of the leached material from the A horizon, particularly the clays and the sesquioxides, are, under normal conditions, redeposited in the B horizon or zone of accumulation. The parent material of the soil in the C horizon may comprise bedrock, transported glacial or alluvial debris, or even soil of a past pedalogical cycle.

Dr. D. W. Cole, of the College of Forestry, University of Washington, furnished the following outline of local soil development processes.

The forest soils in the Cascades are typically podzolic. The heavy vegetation cover tends to restrict erosion and enhance the development of the principal soil horizons. The A horizon is characterized by either an A_1 layer, ranging in thickness from 1 inch to 6 inches, or an ashy-gray A_2 horizon of leached material. The leaching process is aided by the rapid decay of plant debris, producing weak organic acids that can act as complexing agents for the translocation of metallic ions. The B horizon, or zone of enrichment, is characterized by orange-brown soil; the color is due mainly to the redeposition of iron. The zone of maximum organic accumulation on the soil surface occurs between the 4,000-4,500-foot levels in the western Cascades. The soil pH is also maximum at this altitude. The decomposition products of the organic layer and the hydrogen ion activity within this elevation zone result in a rapid translocation of iron from the surface A to the B horizon. If the parent material (C horizon) contains sulfide minerals, the pH is further decreased by the production of weak sulfuric acid in the oxidation environment of the surface A horizon.

Jenny (1941) describes five factors affecting soil formation: parent material, climate, biological activity, relief, and time. With some modification, all these factors have influenced soil development in the Cascades. There is little chemical change between the parent material (mostly bedrock) and the young residual soils. In general, the cold moist marine climate tends to influence the development of soils, which are leached in the surface horizon and possess an iron-rich B horizon. The slope exposure also appears to significantly influence soil development. The north-facing slopes are shaded and wet during much of the year, consequently there is more surface organic accumulation and more extensive leaching than on the south-facing slopes, where there is less water and vegetation and more rapid organic decomposition.

Biological activity is strongly influenced by the climate. Soils developing on steeper slopes tend to have less well-developed and shallower profiles than those on gentler slopes. This is primarily due to constant rejuvenation of the soil by erosional processes. The fairly recent (less than 10,000 years ago) extensive valley glaciation in the range removed the older soil from many slopes, so that in numerous areas the state of recent soil development is poor.

Soil sampling, as an aid to prospecting, can be of considerable value in the Cascades. Care must be exercised to insure that the samples collected are truly representative of the parent bedrock. In much of the range, extensive valley glacial deposits preclude soil sampling below the break in slope profile. In most instances it is easy to differentiate between transported and residual material. When in doubt, however, the sampler should omit the questionable sample rather than risk a possible misleading value. Furthermore, the samples must always be collected from a well-developed B horizon where both total and readily extractable metals are concentrated. The horizons generally can be recognized by the ashy-gray soil color in the A as opposed to the orange-brown to red-brown soil color in the B.

The proper spacing must be selected. Once the principal target zone has been defined, and if extensive cover is present, the sampling interval can be reduced to as little as 50 feet. The correlation of metal content in soils with that of the parent bedrock can be surprisingly accurate. For example, in the Middle Fork of the Snoqualmie River area, a series of mineralized breccia blocks are in fault contact with a series of barren quartz diorite blocks. Outcrop accounts for less than 10 percent of the surface area. Detailed soil sampling on 50-foot spacings was accomplished in traverses paralleling the linear distribution of the mineralized and the barren blocks. The resultant copper geochemical pattern using an anomalous

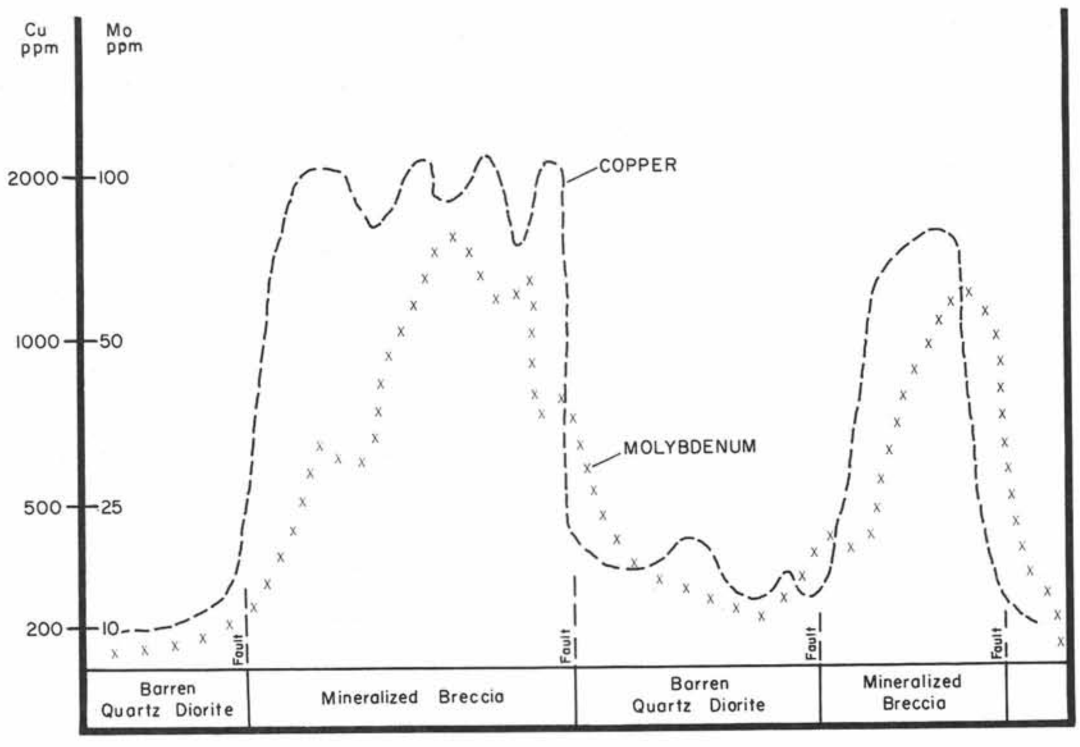

FIGURE 33. — Graph showing the sensitivity of copper and molybdenum total values in soil and reflecting the distribution of metal in bedrock. Upslope geology comprises a series of breccia blocks containing chalcopyrite and molybdenite in fault contact with a series of barren quartz diorite blocks. Data averaged from a geochemical soil survey made in the Central Cascades. Scale: 1 inch equals 200 feet.

threshold of 200 ppm, pinpointed the surface trace of the boundary faults separating the blocks to within 50 feet, which was the sample interval. Many of these faults have since been accurately delineated by drilling and surface trenching. Figure 33 diagrammatically illustrates the above correlation.

The establishment of an anomalous threshold for the total metal values in soils is obviously important. Again, as in the case of stream sediment values, the threshold can vary within short distances according to the geologic background. For example, at the Davis prospect at the end of Ross Lake, the copper-in-soil threshold in the intrusive rocks is 100 ppm. In the overlying volcanic rocks containing the main sulfide zones, the soil background is 200 ppm copper. At the Middle Fork Snoqualmie River property, comprising an all-intrusive rock environment, the background for copper is 200 ppm. Downstream in the same batholith, the soil background drops to 100 ppm copper. The great variation in threshold copper values in the soil is not reflected by molybdenum. In general, 10 ppm molybdenum can be considered to be the threshold value almost anywhere in the range.

Rock Sampling

Geochemical prospecting by sampling and analyzing leached surface rock can be an effective technique in reconnaissance exploration. At many localities in the Cascades this approach is unnecessary, because of the exposure of primary sulfides at the surface. In other areas, particularly those where active K-silicate alteration has occurred, a thin surface layer of supergene altered rock may develop. The depth of leaching varies from a few inches to perhaps as much as 10 feet. Generally, at such localities the downslope soils show a definitive pattern of base metal anomalies if, indeed, base metal is present in the bedrock.

In certain places, further corroboration of the geochemical patterns is advisable by collecting leached rock samples. Such samples, even if thoroughly leached, retain trace amounts of base metal content readily detectable by analytical means. On the average, the relic metal content in leached rock is higher than in the downslope soils. The metal-in-rock values commonly are more reliably interpreted, because the rock is the parent material from which the soils and stream sediments were derived. Also, the rock has not been subjected to the rapidly changing physical, chemical, and biological processes present in soil and stream environments.

In a strictly reconnaissance venture, where the geologist is spot-checking gossans or other leached rock occurrences without benefit of earlier geologic or geochemical data, it is good practice to collect a representative suite of rocks, with particular emphasis on those that are limonitized. The relic base metal content in these rocks often constitutes an important clue as to the content and character of the subjacent hypogene sulfides. Contoured geochemical highs and lows over an extensive area of leached rock often delimit the prime target zones for further exploration. In the Cascades, a rapid and economical method of evaluating many anomalous base metal values in leached rock is by surface trenching with the aid of a portable jackhammer. By this method the source of the anomalous value can commonly be exposed, furnishing the geologist with sufficient information to recommend further work or to cease operations in that particular area.

The study of trace element distribution adjacent to some of the main areas of known copper mineralization in the Cascades may result in the establishment of elemental dispersion patterns suitable to serve as another exploration tool, particularly in areas of heavy cover.

Geophysical Prospecting

The application of geophysical methods in base metal prospecting in the Cascades is a relatively new procedure. Few, if any, data on these surveys are available, as most of the work has been accomplished by private companies. The author's personal experience with geophysical surveys had been limited to a few exploration projects, but even so, several comments are appropriate.

Electrical surveys appear to be the most reliable method of geophysical prospecting yet attempted. The corroboration of induced potential (I.P.) response (including metal factors and percent frequency effects) with total sulfide content in rock has proven excellent in some areas, poor in others. Generally, I.P. traverses must be held to relatively close spacing to produce reliable data for interpretation. This often results in very high field costs, particularly in brushy valleys where lines must be cut. In at least one instance, the source of a strong I.P. anomaly is suspected of being ionized warm-spring water circulating below the water table. Other types of resistivity surveys might yield results comparable to those of I.P. at a considerably lower cost. Self potential surveys appear to be of little value.

Ground magnetics have proven to be a useful interpretive tool in areas where a relation between chalcopyrite and pyrrhotite deposition has been established. The results of air-borne magnetometer surveys over rugged mountainous terrain indicate that large areas of pervasive sulfide mineralization can be crudely delineated. However, the value of this type of approach in a relatively small area such as the Cascades is questionable.

Research is currently being conducted on other types of geophysical methods that could be applied effectively to Cascade exploration. In this area of hundreds of square miles of mostly covered terrain (particularly in the South Cascades), geophysical prospecting could become an invaluable tool for the exploration geologist.

APPENDIX II

EXPLORATION PROBLEMS IN THE CASCADE RANGE

Economic Geology and Land Utilization

For many years the Cascade Range of Washington, particularly the North Cascades, has been embroiled in public controversy over land management and utilization. This has been precipitated mainly because the Cascades include some of the finest alpine terrain in the United States. Recently, the problem has been highlighted by recommendations of a Federal Government Study Team suggesting the establishment of a North Cascades National Park and several satellitic wilderness areas as the best means of protecting the scenic resources.

The problems of public land utilization are numerous and complex. Conservationists advocate the concept of preservation of scenic resources, whereas the industrial interests promote the concept of multiple use. Each has a legitimate cause; however, these causes should be kept in perspective. Current studies have not fully revealed the mineral potential in the North Cascades, even though the U.S. Geological Survey and the U.S. Bureau of Mines are conducting a 3-year evaluation program in part of that area. On the other hand, several promotional groups have distributed information, based on little factual data, indicating the existence of enormous reserves of metal in the North Cascades. A reasonable approach to these problems must be found, hopefully, without emotional bias.

The proper utilization of these public lands poses both a problem and an obligation to the exploration geologist. In evaluating the area for mineral potential, he should conduct his exploration with realism based on discretion. Modern concepts and techniques should be applied. There is no justification for strictly promotional operations without heed to well-established principles of conservation and land management.

With the advent of a new era of mineral exploration in the Cascades, compliance with the above concepts is imperative. Mining companies have recognized the great value of good public relations. Because most of their work is conducted on public lands, all public interests should be considered. It is to be hoped that in recent years the image of the mining industry has improved. However, mining still suffers from its past record when, in many instances, little or no regard was paid to land conservation.

The utilization problem has reached critical proportions in the Cascades, as shown by the current conservation battles. Those in the mining industry who desire favorable public opinion must take a stand for propriety and prudence. This can be accomplished by discouraging indiscriminate alteration of the landscape where such work is conducted for promotional purposes only; by standing against improper staking; by publishing factual data based on accepted scientific procedures when informing the public as to the evaluation of potential of contested public domain; and, finally, by securing competent personnel for directing field operations. This latter point may appear obvious, but the mining history of the Cascades, in common with that of other areas, is replete with so-called "professional" men who have been poor representatives of the mining industry.

Land Classification

Three major types of Federal lands exist in the range (Fig. 1, on page 11). The exploration manager must be aware of these classifications and of the possible restrictions pertaining thereto.

The National Forest lands, administered by the United States Forest Service, are divided into two main categories; namely, multiple use and wilderness. There are many other, minor, land classifications, such as limited use areas, forest camps, road rights-of-way, and military reservations. Details concerning minor land classes can be obtained from various Federal agencies. Forest lands designated as multiple use are governed by the Federal Multiple Surface Use Act of 1955 and various older mining laws. Prospecting, claim staking, exploration operations, and mining are permitted on these lands with few restrictions. The local Forest Service agency must be consulted, however, if major changes to the landscape, such as road building, are contemplated. As always, adherence to safety and fire regulations in the forest is required.

The wilderness and primitive areas, both established and proposed, are open to prospecting and claim staking until 1983. These areas are administered under the Wilderness Act of 1964. The act prohibits commercial operations in all Wilderness-type areas, with the exception of prospecting and exploration-development work related to mining. At the end of 1983, however, these areas will be closed to further mineral entry. The claims and mining operations existing at that time will be permitted to remain, provided all work is conducted within the terms of strict regulations.

Under the present Wilderness Act, mechanical means of transport (e.g., helicopters, trail bikes, etc.) are prohibited for prospecting in wilderness areas. After establishing a claim, however, applications for special use permits can be requested from the Forest Service for use of mechanical conveyances for ingress or egress to the claim site. These permits are issued only when such transport is proven to be an absolute necessity to complete the work. Pack horses commonly are sufficient to move equipment for a small exploration venture, whereas a helicopter is a necessity to move heavy drill equipment for a major exploration project.

It is important to work closely with the Forest Service to insure compliance with all rules and regulations. Exploration in wilderness and primitive areas is possible, but is inherently more restrictive in physical scope than in multiple use areas, due to the nature of the land classifications.

National Park areas, administered by the National Park Service under the U.S. Department of the Interior, are closed to mineral entry.

For a more comprehensive discussion of mineral rights in the Cascades, the reader is referred to Washington State Division of Mines and Geology Information Circular No. 36, "Mineral Rights and Land Ownership in Washington," by Wayne S. Moen, 1962.

Field Operations

The rugged alpine terrain in the range commonly presents difficult access problems. Travel in these areas generally requires considerable care, and all field crews should be trained to cope with mountaineering emergencies. Traverses should be planned to minimize the risk of exposure to rockfall or avalanche. Personnel should not work singly, except within the immediate camp area. On long difficult traverses, a minimum field party of three is recommended. Then, in the event of an accident to one, the second can seek help while the third remains with the injured. All personnel should have a fundamental knowledge of first aid procedures.

Snowslide danger in the range is greatest during the early spring. Destructive power of these avalanches cannot be overestimated. Spring field work should be planned so that the high avalanche areas are avoided until the danger has abated. As a compensating factor, much valley work is more feasible in the spring, when snow still covers the brush.

In general, because of the cold wet climate of the Cascades, field work is seasonal in nature. On the average, one can anticipate about a 5-month field season in the North Cascades, an 8-month season in the Central Cascades, and a 10-month season in the extreme southern part of the range. These periods vary considerably, depending on the elevation and exposure of the work area. Above 6,000 feet in the North Cascades, new snow can be expected at any time, even at the height of the summer season. Extensive flooding may occur in the spring and fall, causing damage to access routes.

Operation of helicopters in the range is difficult, but their use is an invaluable aid in conducting reconnaissance operations or servicing inaccessible drilling projects. At this time, the Bell G3B-1 is the most versatile ship for Cascade work (provided pay loads of not more than 750 pounds are anticipated). Its sensitivity to the constantly changing air conditions provides an extra margin of safety to the operation. Obviously, only the most experienced pilots should be assigned to Cascade projects.

When on reconnaissance, helicopter flight plans should be filed to insure efficient search and rescue operations in the event of accident or breakdown. Adherence to a flight plan is difficult by the very nature of reconnaissance work, but safety alone dictates that some such procedure be established. Emergency helicopter fuel supplies and survival caches should be considered if regional helicopter use is contemplated. Personnel working with helicopter operations should maintain exact schedules for pickup or departure. Also, they should be equipped to bivouac or to walk out in the event weather conditions prohibit completion of schedules. In this regard, the party chief can use the helicopter to scout routes of questionable traverses in order to insure that the ground crews can arrive on time at proposed pickup points. All personnel should carry brightly colored flagging to facilitate their being spotted from the air.

During the moving of heavy equipment, ground-to-air radios should be employed. In the event radios are not available, the field crew should be thoroughly trained in hand signal techniques.

Cost Estimates

It is recognized that any cost estimates are extremely flexible. However, past experience in the Cascades has indicated that general cost/unit data can be projected to aid in project planning. The reader must be cautioned to give these data wide latitude, as much depends upon the experience of the field crew, weather, topography, overburden, brush, and other variables.

1. Geologic mapping		
a. Reconnaissance	(2 inches to the mile scale)	\$100/square mile
b. Reconnaissance	(1:1,000 scale)	\$500/square mile
c. Detailed	(1:400 scale)	\$100/acre
d. Detailed	(1:100 or less)	>\$500/acre
2. Geochemical sampling - Stream sediment		
a. Reconnaissance	(1-mile sample spacing)	\$10/sample
b. Reconnaissance	(high-density spacing)	\$4/sample
3. Geochemical sampling - Soils		
a. Reconnaissance	(sample intervals 1,000 feet)	\$4/sample
b. Detailed	(sample intervals 200 feet)	\$1/sample
4. Geophysical prospecting		
a. I.P. survey	(average 200-ft. dipole spacing)	\$1000/line mile
b. Resistivity	(same average spacing)	\$300/line mile
c. Magnetics - ground	(200-ft. stations)	\$100/line mile
d. Magnetics - ground	(50-ft. stations)	\$400/line mile

5. Helicopter - In general, the costs will range from \$100 to \$135/flight hour. No standby time is charged if a minimum daily rate (>2 hours) is flown. The prices are obviously lower per flight hour on extended contract, and the highest on short-term daily flights.

6. Drilling		
a. Packsack	(own drill and equipment)	\$4/ft.
b. Contract	(Ax size - all-inclusive costs)	\$7/ft.
c. Contract	(Bx size - all-inclusive costs)	\$8/ft.

Note: This is difficult to estimate, as drill prices depend on guaranteed footage contracts.

7. Personnel room and board - An average cost for maintaining a crew in the field is \$5.50/man day.

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