

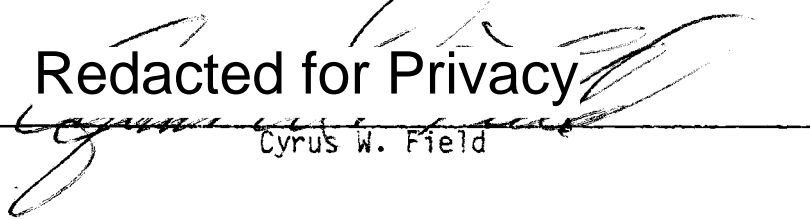
AN ABSTRACT OF THE THESIS OF

Sara G. Power for the degree of Doctor of Philosophy in  
Geology presented on September 25, 1984.

Title: The "Tops" of Porphyry Copper Deposits - Mineralization and  
Plutonism in the Western Cascades, Oregon

Abstract approved:

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Cyrus W. Field

The mining districts of the Western Cascades and their associated epizonal plutons and locally extensive zones of hydrothermally altered rocks are roughly parallel to the northerly trend of the Quaternary High Cascades. The volcanic rocks range in age from Oligocene (Washougal and Bohemia districts) to mid-Miocene (North Santiam, Detroit Dam, Quartzville, and Blue River districts). These volcanic rocks are intruded by numerous plutons of intermediate composition. Both plutonic and volcanic rocks have calc-alkaline affinities and the chemical composition of the intrusions resembles that of plutons from island arc terrains. Ages of plutons in the Washougal (20 m.y.), North Santiam (13 m.y.), Blue River (13 m.y.), and Bohemia (22 m.y.) districts are consistent with the geology of these areas. Ages of hydrothermal alteration in the Washougal (19 m.y.) and North Santiam (11 m.y.) districts suggest a direct genetic relationship between mineralization and spatially associated plutons

of granodiorite and quartz diorite porphyries and porphyritic granodiorite, respectively.

Hydrothermal alteration of plutonic and volcanic host rocks in and adjacent to the mining districts of the Western Cascades is dominated by the propylitic assemblage. Argillic and phyllic assemblages are more local and are controlled by structure, especially near the base and precious metal-bearing vein deposits. Potassic alteration is associated with porphyry-type mineralization in the Washougal and North Santiam districts, and with a one sample Cu-Mo anomaly in the Bohemia district. Vein-type mineralization is largely defined by subequal amounts of Cu and Zn together with lesser quantities of Pb, whereas that of the porphyry-type is dominated by Cu.

Sulfur isotope compositions of the sulfide minerals range from -5.1 to 5.0 permil, and average about 1.7 permil. This relatively narrow range of  $\delta^{34}\text{S}$  values near 0 permil is consistent with a magmatic derivation for the sulfur. Isotopic temperature estimates indicate sulfide deposition in veins at 200° to 500°C and up to 675°C in porphyry-type environments. Homogenization temperatures and salinities of fluid inclusions in vein quartz range from 167° to 319°C and from 0 to 18 wt percent NaCl, respectively. In contrast, those of halite-bearing inclusions associated with breccia pipes and potassically altered plutons exceed 386°C and 30 wt percent NaCl. The depth of cover at the time of mineralization is estimated to range from 740 m in the North Santiam district to 1800 m in the Washougal district.

Geologic and geochemical evidence collectively suggest that porphyry-type copper and molybdenum mineralization may underlie many if not all mining districts of the Western Cascades.

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The "Tops" of Porphyry Copper Deposits -  
Mineralization and Plutonism in the Western Cascades, Oregon

by

Sara Glen Power

A THESIS

submitted to

Oregon State University

in partial fulfillment of  
the requirements for the  
degree of

Doctor of Philosophy

Completed September 25, 1984

Commencement June 1985

APPROVED:

Redacted for Privacy

Professor of Geology in charge of major

Redacted for Privacy

Head of Department of Geology

Redacted for Privacy

Dean of Graduate School

Date thesis is presented September 25, 1984

Typed by Mary Ann (Sadie) Airth for Sara Glen Power

## ACKNOWLEDGEMENTS

This dissertation is the culmination of a study of mineralization in the Western Cascades which began in 1966 under the direction of Cyrus W. Field. Many of the studies in this region were partially funded by the Hanna Mining Company and by the Oregon Department of Geology and Mineral Industries. These previous studies provided maps, samples, and geologic interpretations which were essential to this dissertation. These former colleagues include Jay W. Hammitt (Brattain district), David A. McLean (Detroit Dam area), Steven R. Munts (Quartzville district), James K. Munzert (Brattain district), Martha Ness (South Umpqua district), James P. Olson (North Santiam district), Thongchai Pungrassami (Detroit Dam area), Michael P. Schaub (Bohemia district), Alexander Schriener, Jr. (Washougal district), Richard J. Shepard (Washougal district) and Scott W. Tregaskis (Bohemia district). Geologic information relevant to recent exploration programs and permission to visit mineral properties and to sample diamond drill core were kindly provided by F. Thomas Bourns, Arthur G. Humphrey, and James P. Matlock of the Amoco Minerals Company; Russell C. Babcock Jr. and Phil R. Fikkan of the Bear Creek Mining Company; Robert A. Metz of the Duval Corporation; Donald J. Decker and Michael B. Jones of the Freeport Exploration Company; and George Atiyeh of the Shiny Rock Mining Company. Paul E. Hammond of Portland State University generously provided his unpublished information concerning several mineral deposits and the

volcanic stratigraphy of southern Washington. Roger Ashley of the U.S. Geological Survey shared some unpublished major oxide data from the Spirit Lake pluton in Washington.

Parts of this dissertation were reviewed by Joshua D. Cocker, Harold E. Enlows, Ronald G. Senechal, Edward M. Taylor, and William H. Taubeneck of Oregon State University. A research grant from the Oregon Department of Geology and Mineral Industries facilitated the acquisition of much of the geochemical data, compilation of geologic maps and analyses, and completion of a summary report. Additional financial support was provided by the American Federation of Mineralogical Societies Scholarship Foundation.

Most of this dissertation will be included in the summary report for the Oregon Department of Geology and Mineral Industries which is coauthored by Cyrus W. Field. I would like to thank Cy for his often extensive revisions of some chapters; indeed the introduction chapter and the preface to the discussion of individual mining districts are largely his work.

I would like to thank Sadie Airth for typing the text and Therese Belden for typing Appendices 2 and 3.

On a personal note, I would like to thank my sister, Julia Serences, and my husband, Bill Storch, for their continuous unconditional support throughout initial formation to completion of this research effort.

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# THE "TOPS" OF PORPHYRY COPPER DEPOSITS - MINERALIZATION AND PLUTONISM IN THE WESTERN CASCADES, OREGON

## INTRODUCTION

The Cascade Range of western Oregon and Washington is defined by a linear trend of Quaternary stratovolcanoes that extends for a distance of about 650 miles from Mt. Lassen and Mt. Shasta in northern California to Mt. Garibaldi in southern British Columbia. For more than a century this region has been accorded international pre-eminence because of its spectacular alpine scenery, dense forests of merchantable timber, and diversity of youthful to recent volcanic features. Accordingly, these attributes are well-known to tourists, foresters, and volcanologists. In contrast, the numerous but largely inactive mines and prospects that are sporadically clustered in districts along the western foothills of the Cascade Range throughout central and northern Oregon and southern Washington are little known beyond the provincial confines of the Pacific Northwest. Historically, the mines were small and exploitation, chiefly for gold and silver, was intermittent. Today, these mining districts are used principally by weekend campers, rockhounds, and gold panners for recreational purposes. The original discoveries were made between the late 1850's and the turn of the century by prospectors who found placer gold in the stream beds and traced its source to veins exposed on nearby mountain slopes. Since the inception of mining activity, gold has been the most important metallic commodity produced from these mines (about 90 percent of revenues) with much smaller

contributions derived from silver, lead, copper, and zinc. The total value of recorded mineral production from all mines of the Western Cascades subprovince is less than \$1,500,000 according to data provided by Brooks and Ramp (1968), Mason and others (1977), and Moen (1977). This is a relatively insignificant amount as compared to that of the better known multi-billion dollar districts of the western U.S. such as those at Bingham, Utah; Butte, Montana; and Morenci, Arizona. The Western Cascades mineral province has been largely neglected by the mining industry because of the trivial production record, paucity of up-to-date geologic information, and general lack of other inducements upon which modern exploration programs are conceived and implemented.

This dissertation should encourage a renewal of exploration efforts in this region on the basis of historical records and the interpretations of new geologic and geochemical data presented herein. The value of past mineral production (less than \$1,500,000) is but a small fraction of the value of potential ore (more than \$500,000,000) that remains at depth within these districts as they are presently defined. In contrast to past mineral production that was confined to small vein-type deposits of gold, silver, lead, zinc, and copper, future exploration efforts will be directed to the mining of larger and lower grade porphyry-type deposits of copper with recoverable byproducts of silver, gold, and possibly molybdenum. The great mining districts of Bingham, Butte, and Morenci, as previously noted, derive most of their current production and reserves of ore

from porphyry-type deposits of copper and byproduct molybdenum, silver, and gold. However, it is of historical and scientific interest to note that the discovery and (or) earliest production of minerals at each of these districts, and at many others throughout the world, was based on placer gold found locally in stream beds by prospectors (Boutwell, 1905; Weed, 1912; Moolick and Durek, 1966). The mining operations at many districts throughout the Western Cordillera have exhibited a nearly consistent evolutionary sequence of development from early surficial gold placers, through subsequent subsurface mine workings for small, high-grade vein and replacement deposits of base and precious metals, to later and larger open-pit or subsurface mines utilizing low-grade porphyry-type deposits of copper and other byproduct metals. The latter category, the porphyry-type deposits, offers the greatest potential for significant future mineral production from the Cascade Province of Oregon and Washington.

Possible interrelationships between processes of volcanism, plutonism, geothermal activity (hot springs, geysers, and fumaroles), and the formation of metallic mineral deposits have been subjects of geologic investigation and speculation for many years. A widespread resurgence of interest in these studies has been generated by recent public awareness of energy and mineral resources, the foundation of any industrialized society, and particularly as they relate to shortages in times of ever-increasing demand. Justification for such investigations is at least two-fold. First, there are basic

scientific objectives which seek to provide a better understanding of specific geologic processes, and especially those that may now be integrated with modern plate tectonic theory. Second, there are practical objectives such as the formation of new concepts or techniques of exploration which may result in the discovery of additional or totally new sources of energy and minerals. Repercussions of the latter, be they economic, strategic, or both, may have regional, national, or global significance. The Western Cascades subprovince provides a nearly ideal setting for the study of mineral deposits associated with igneous rocks. Although volcanic rocks predominate throughout most of this region, there is a unique spatial and temporal association of plutonic rocks and mineral deposits within each of the mining districts. Because the terrain is relatively young, less than 40 m.y. in age, it has not been subjected to the additional geologic complexities of structural deformation and regional metamorphism as may characterize older provinces of the Pacific Northwest. Physical access to most parts of this region is readily obtained by county, Federal, and private roads of variable quality and by trails. Although much of the bedrock is covered by alluvium, soils, and vegetation, geologic mapping and sample collecting are accomplished with minimum difficulty as a consequence of natural exposures formed by erosion and moderate to steep topography and man-made exposures provided by road-cuts, subsurface mine workings, and diamond drill core from recent exploration.

Emphasis throughout the thesis is directed to the associated and presumably cogenetic processes of plutonic magmatism and hydrothermal mineralization. Locations of the mining districts are illustrated in Fig. 1 as are those of other geologically important features such as the porphyry-type deposits, granitic plutons of Tertiary age, areas of hydrothermal alteration (Peck and others, 1964), hot springs (Bowen and Peterson, 1970), and the Quaternary stratovolcanoes which define the crestal axis of the modern High Cascades. Note the singular coincidence of the plutons and areas of alteration with the mining districts, and the generally subparallel and north-trending alignment of districts, plutons, alteration, and hot springs to the stratovolcanoes farther to the east. Probably both plutons (or magma chambers) and mineral deposits (or active hydrothermal systems) are present at depth beneath many of those volcanoes. Mineralization in the districts was accomplished by the convective circulation of hot aqueous fluids along preexisting fractures. These hydrothermal fluids were heated by and possibly derived from nearby intrusions as they underwent cooling and crystallization. In essence, the mineral deposits and larger associated zones of hydrothermally altered rock (see Figure 1) are the vestiges of paleogeothermal activity, whereas the nearby hot springs represent similar contemporary activity expressed by reservoirs of magma or cooling intrusive rocks at depth. The epithermal to mesothermal vein-type deposits of base and precious metals that characterize the mining districts of the Western Cascades are probably the uppermost or high-level extensions of porphyry-type

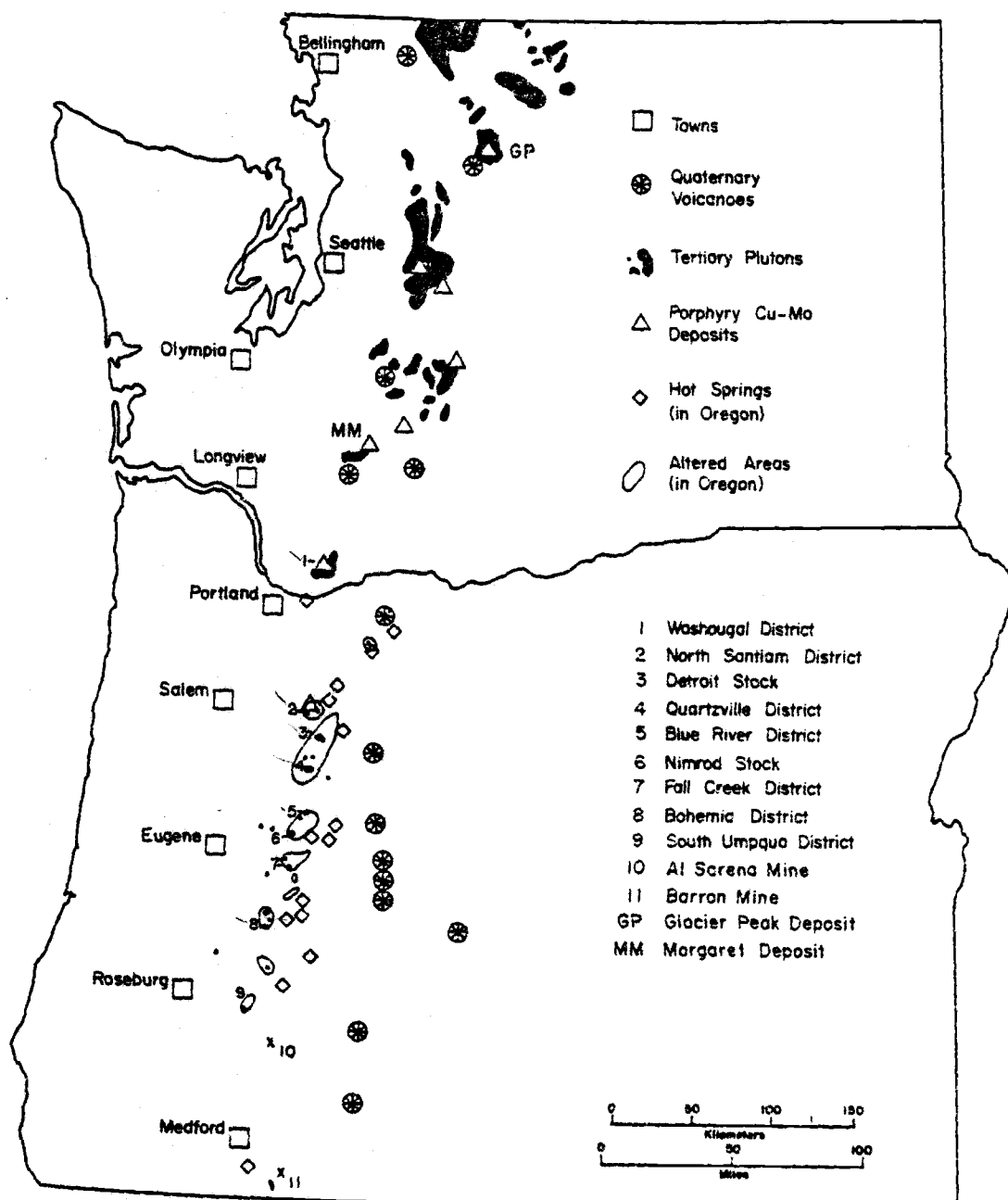


Figure 1. Distribution of mining districts, areas of alteration (Peck and others, 1964), and hot springs (Bowen and Peterson, 1970) in the Western Cascades and Quaternary stratovolcanoes, Tertiary plutons, and porphyry-type deposits in the Cascade Range.

deposits at depth. This conclusion is based upon observations of the geology, mineral deposits, and distributions of metals and minerals in these districts and upon comparisons of these data to the models of Burnham (1967), Lowell and Guilbert (1970), Rose (1970), Norton and Cathles (1973), Sillitoe (1973), and other investigators who have examined the interrelationships of plutonism, volcanism, and mineralization in porphyry-type hydrothermal systems. The first recognition of porphyry-type mineralization in the Cascade Range was at the Glacier Peak copper-molybdenum deposit in northern Washington by at least the early 1950's (Hunting, 1956), and other occurrences have been reported from elsewhere in the Washington Cascades over the succeeding years (Grant, 1969; Field and others, 1974; Armstrong and others, 1976; Moen, 1977; and Hollister, 1979). These porphyry-type deposits form a northerly continuation of the north-trending array of mining districts in the Western Cascades of Oregon and southern Washington. The linear trend of deposits and districts, as shown in Figure 1, is highly suggestive of a single metallogenetic province, and this inference is further supported by recent discoveries of porphyry-type mineralization in the Washougal district of southern Washington and North Santiam district of northern Oregon. On the basis of these facts and inferences, and from other data such as north to south changes in the size and complexity of plutonic intrusions, extent and types of hydrothermal alteration, distributions of ore and gangue minerals, metal ratios, types of fluid inclusions, and sulfur isotopic ratios, one may conclude that porphyry-type deposits

probably underlie other mining districts of the Western Cascades. Provided this interpretation is correct, the geologic differences exhibited by the plutonic rocks and mineral deposits from district to district are the result of differing levels of erosional exposure. Thus, the porphyry-type deposits, if present, become progressively deeper from north to south. Accordingly, geologic investigations of the volcanic rocks, plutonic rocks, and mineral deposits from the mining districts of the Western Cascades offer three-dimensional insight to the salient features of hydrothermal systems. The results are potentially of both scientific and practical importance, and particularly the latter with respect to the exploration for deeply buried mineral deposits. Fluid inclusion and sulfur isotope studies have provided estimates of the depths and temperatures at which porphyry-type mineralization took place in the Western Cascades. These data support the model of a Cascade porphyry system presented herein.

## REGIONAL GEOLOGIC SETTING

The Cascade Range is a volcanic arc which has been active from late Eocene time to the present. The central and southern parts of the Cascade Range can be subdivided into two distinct physiographic subprovinces: the Western Cascades and the High Cascades. The High Cascades are dominated by Pleistocene to Recent volcanic rocks and stratovolcanoes. The Western Cascades consist of older volcanic flows, pyroclastics, and sedimentary rocks, and associated intrusions of Tertiary age, which have been faulted, gently folded, and deeply dissected. These two subprovinces converge and overlap north of Mt. Hood. Quaternary stratovolcanoes overlies older Tertiary and pre-Tertiary rocks in both the southern and northern parts of the Cascade Range.

The tectonic setting of the Cascades is shown in Figure 2. The subparallel alignment of the volcanoes to the continental margins is the best evidence of convergence between the North American and Juan de Fuca plates. In addition, the magnetic stripes disappear under the continental edge, indicating that subduction has taken place in the past and may be active today. However, other features of an active convergent plate boundary are notably lacking; seismic activity is low and a well-developed trench is not apparent. The absence of these features may indicate that subduction is now taking place at a very slow rate and that the trench is filled with sediment. An alternative hypothesis is that the North American and Juan de Fuca plates have been coupled for as long as the last seven million years

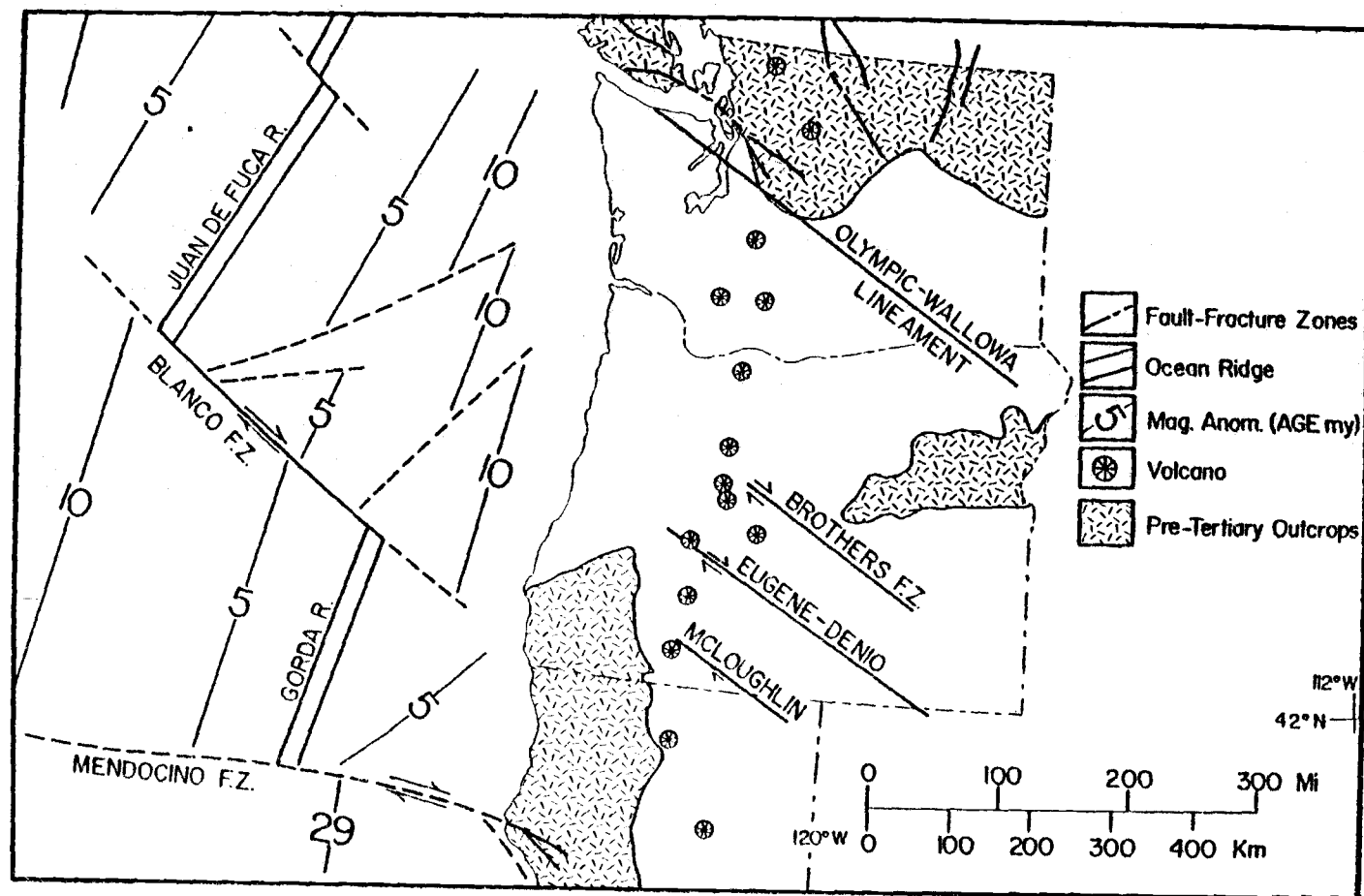


Figure 2. Tectonic setting of the Cascade Range (from Atwater, 1970; Field and others, 1974; and Simpson and Cox, 1977).

(Atwater, 1970). Recent paleomagnetic studies indicate that the geologic and structural framework of the Pacific Northwest is further complicated by the tectonic rotation and translation of discrete crustal segments. The results of Simpson and Cox (1977), Magill and Cox (1981), Bates and others (1981), and other investigators cited by these authors suggest that parts of the Cascade Range have undergone a clockwise rotation of as much as  $33.5^{\circ}$  since Oligocene time (about 23 to 38 m.y. ago) and possibly by as much as  $75^{\circ}$  since Eocene time (about 39 to 55 m.y. ago). Supportive of the paleomagnetic evidence is the apparent convergence of linear trends defined by the Tertiary plutons and the Quaternary stratovolcanoes depicted in Figure 1, which imply a clockwise rotation of about  $14^{\circ}$  over the past 20 m.y.

Other factors, in addition to possible structural discontinuities, may influence the distribution and kinds of rocks and ores in this region. Because exposures of pre-Tertiary rocks are confined to northern Washington, southern Oregon, and the central to eastern parts of these states (see Figure 2), it has been suggested that the central part of the Cascade Range may be underlain by a thin layer of basaltic oceanic crust rather than by a thicker sequence of older sialic continental crust. Possible differences in the composition, thickness, and age of the underlying crustal sequence might influence the compositions and volumes of younger volcanic and plutonic rocks and the abundances and types of metals in associated mineral deposits (Robyn and others, 1981).

Regional stratigraphic correlations in the Cascades are difficult as a result of the great lateral variation in deposits typical of a volcanic terrain. Recent studies have indicated that Tertiary volcanism has not been continuous but periodic. Episodes of intense volcanism were essentially synchronous throughout much of the Cascade Range (McBirney and others, 1974), the northwestern United States (Armstrong, 1978), and the world (Kennett and Thunne1, 1975; Vogt, 1975). Radiometric age determinations reported by Sutter (1978) have aided in correlations of periods of volcanism with previously defined stratigraphic units in Oregon. Unfortunately, comparable information is not available for volcanic rocks of southern Washington. The principal periods of volcanism recognized in the Cascades, along with corresponding stratigraphic units of the Western Cascades of Oregon are presented in Table 1. Volcanic rocks of the Cascades are underlain by pre-Tertiary rocks in northern Washington and southern Oregon (Fig. 2). In central and northern Oregon, marine sedimentary rocks of Eocene age underlie volcanic rocks of the Cascades (Peck and others, 1964). Age determinations for the oldest volcanic rocks of the range are less than 40 m.y. old, and are separated from underlying Eocene rocks by an angular unconformity (McBirney, 1978). Oligocene to early Miocene volcanism is represented by the Little Butte Volcanic Series in Oregon and by the Ohanapecosh Formation (?) in southern Washington. The earliest magmatic products of this period are basaltic and andesitic lavas followed by a variety of tephra deposits. In the central Oregon Cascades, rocks of this age

Table 1

Episodes of volcanism and approximate stratigraphic equivalents  
in the Cascade Range of Oregon

(modified from McBirney, 1978, and Sutter, 1978).

<u>Volcanic Episode</u>	<u>Stratigraphic Equivalent</u>
Quaternary (Cascadian) 0 - 1.8 m.y.	High Cascade Volcanics
Pliocene (Fijian) 3 - 5.5 m.y.	Outerson Formation (?) High Cascade Shield Basalts
Late Miocene (Andean) 8 - 11 m.y.	Elk Lake Formation
Middle Miocene (Columbian) 14 - 17 m.y.	Sardine Formation
Oligocene-Early Miocene 19 - 40 m.y.	Little Butte Volcanic Series (possibly the Ohanapecosh Formation of southern Washington)

show a trend of iron enrichment that is greater than that of the younger lavas (White and McBirney, 1978). This trend becomes less tholeiitic and more calc-alkaline with time. Mid-Miocene volcanism was predominantly andesitic and is represented by the Sardine Formation in Oregon and by the Stevens Ridge and (or) Fives Peak Formations in southern Washington. Volcaniclastics make up the bulk of the Sardine Formation. White and McBirney (1978) have speculated that most of the hypabyssal plutons and their surrounding hydrothermal alteration halos coincide with volcanic centers of this magmatic episode. A distinct episode of Late Miocene volcanism (9 to 10 m.y.) has been recognized on the basis of radiometric age determinations (McBirney and others, 1974). However, the volcanic rocks formed during this later episode are difficult to distinguish from older rocks of the Sardine Formation. Several plutons in the Western Cascades were intruded during this magmatic episode. Because the centers of Pliocene and Pleistocene volcanism shifted to the east, younger volcanic rocks are rarely found in the Western Cascades.

The Central Cascade Range occupies a large north-trending downwarp (Peck and others, 1964). The High Cascades have been downfaulted relative to the Western Cascades (Thayer, 1936) and may occupy a graben (Taylor, 1968, 1980, 1981; Allen, 1965). Quaternary volcanoes are aligned parallel to the north-south trend of this structural downwarp, as are the older volcanic belts, hypabyssal plutons, and the areas of mineralization.

Most of the rocks in the Western Cascades have been gently deformed by broad northeast-trending folds. This deformation is post-Late Eocene and pre-Pliocene. The paucity of bedrock exposures, stratigraphic marker horizons, and reliable strikes and dips make it more difficult to precisely determine the period or periods of deformation.

Northwest-trending fault and fracture systems are common in the Western Cascades (Peck and others, 1964). These faults are particularly well documented in mineralized areas, because they commonly served as channelways for the hydrothermal systems. Thus, the faults may be as old as Miocene in age and in some areas may have formed as recently as Pliocene or Quaternary. According to Lawrence (1976), these faults may be related to the northwestern termination of Basin and Range fault structures in Oregon.

The mining districts of the Western Cascades, and their associated epizonal plutons and locally extensive zones of hydrothermally altered host rocks, are roughly parallel to the northerly trend of the Quaternary volcanoes that topographically define the High Cascades as illustrated in Figure 1. However, because the centers of volcanism have shifted to the east with time, it is probable that the associated centers of plutonism and hydrothermal activity have also migrated to the east, but remain largely covered. Many active hot springs (Bowen and Peterson, 1970) lie to the east of the hydrothermal mineral deposits that comprise the mining districts of the Western Cascades. Presumably they are the surface manifestations of

more extensive hydrothermal systems at depth, although structurally they may be related to the fault or faults that downdropped the High Cascades (Pitts, 1979). Moreover, the presence of hot spring, fumarolic, and solfataric activity on or near Mt. Baker, Mt. St. Helens, Mt. Hood, Mt. Lassen, Mt. Shasta, and probably other volcanic mountains amply documents an association of hydrothermal systems with the Quaternary stratovolcanoes, as is consistent with the model proposed by Sillitoe (1973).

Historically, and as noted in the introduction, the productive mineral deposits of the Western Cascades have been epithermal to mesothermal veins in bedrock containing base and precious metals and derivative placer deposits of gold. However, recent exploration and diamond drill programs have revealed the presence of porphyry-type mineralization in the Washougal district of southern Washington and the North Santiam district of northern Oregon. Volcanic and plutonic host rocks to the principal mines and prospects in each of the districts have been subjected to widespread propylitic hydrothermal alteration (Peck and others, 1964) as illustrated in Figure 1. Smaller areas of phyllic and potassic alteration are locally present in most of the districts, and these are potentially significant because of their association with porphyry-type deposits elsewhere throughout the cordillera of North and South America (Lowell and Guilbert, 1970; Field and others, 1974; and references cited therein).

## VOLCANIC ROCKS

Volcanic rocks are the hosts for most of the mineralization in the Western Cascades. The most common rock types in mineralized areas include multi-lithic breccias (lahars), tuff-breccias, ash-flow tuffs, lapilli tuffs, and flows of andesite and basalt. Rock types differ little between districts, although their relative abundances and stratigraphic positions are variable. Minor flows of dacite are found in most areas, and a distinctive rhyodacite flow has been described by Munts (1978) in the Quartzville district. Welded tuffs have been observed in the North Santiam and Quartzville districts by Olson (1978) and Munts (1978), respectively.

Rock sequences of the districts have characteristics of the central and proximal facies of volcanic centers. Features that most of the districts have in common with the central zone are dikes, sills, breccia pipes, stocks, and hydrothermal alteration. Many of the districts have the "bewildering structural and lithologic diversity and their pervasive alteration" which is characteristic of central vent areas according to Williams and McBirney (1978, p. 312). However, the lavas, lahars, and tuffs are more indicative of the proximal facies. Moreover, country rocks of the Detroit area are dominated by a volcanic-sedimentary sequence that may be representative of a distal facies. Although the Detroit stock would indicate a central facies, perhaps this large intrusion was the subsurface expression of a later episode of volcanism, the products of which

either have been removed by erosion from the central vent area or were deposited elsewhere.

### Petrochemistry

Flow rocks from mineralized areas in the Western Cascades are predominantly basalts, basaltic andesites, and andesites, although minor flows and dikes of dacite and rhyodacite are found in most districts. Almost all flow rocks are porphyritic. Phenocryst mineralogy is remarkable uniform throughout the region. Mafic flows (basalts, basaltic andesites and andesites) commonly contain phenocrysts of plagioclase feldspar (andesine and labradorite) and pyroxene (usually augite, although hypersthene predominates occasionally). Phenocrysts of iron-titanium oxides are common in flows of the Blue River, Washougal, and North Santiam districts. A few basalt flows of the Bohemia and Washougal districts contain rare phenocrysts of olivine. One andesite flow in the North Santiam district contains a few small phenocrysts of quartz. Phenocrysts of silicic flows (dacites and rhyodacites) are somewhat more variable between districts, and may include potassium feldspar, quartz, iron-titanium oxides, and green hornblende, in addition to ubiquitous plagioclase feldspar. Phenocrysts of orthoclase and quartz are present in dacites from the North Santiam and Quartzville districts. Dacite in the Washougal district contains phenocrysts of plagioclase feldspar, quartz, and iron-titanium oxides. Muscovite and green hornblende are found in "quartz latites" from the North Santiam district and are

probable the result of hydrothermal alteration. These flows have been altered to an assemblage of quartz and sericite but were probably andesites prior to alteration.

Chemical analyses have been obtained for a variety of flow rocks from mineralized areas of the Western Cascades. These data are listed in Appendix 2, and are graphically summarized on Harker variation diagrams in Figure 3. Sample representation is probably biased in favor of the less common silicic flows. The silicic flows are visually distinctive and were almost invariably selected for chemical analysis whereas the more common mafic flows are represented by fewer chemical analyses relative to their actual abundance. Nonetheless, basalts, basaltic andesites, and andesites comprise about 76 percent of the volcanic rocks analyzed, and the remainder are dacites and rhyodacites. Samples of rhyolite were not analyzed.

The alkali-lime index (Peacock, 1931) for all samples of volcanic rock is 61.8, which indicates that these rocks contain slightly more CaO, relative to total alkalis ( $K_2O + Na_2O$ ) at a given silica content, than do most calc-alkaline suites. Chemical trends of the major oxides given by Harker variation diagrams (Figure 3) are similar to those shown by other calc-alkaline suites. Constituents such as  $FeO_t$ ,  $Al_2O_3$ , CaO, MgO, and  $TiO_2$  decrease with increasing content of  $SiO_2$ , whereas  $K_2O$  and  $Na_2O$  increase. Concentrations of  $FeO_t$  and  $Al_2O_3$  show the largest range of values with respect to  $SiO_2$ . Much of this spread is caused by samples from the Bohemia district which have lower contents of  $Al_2O_3$  and higher contents of  $FeO_t$  relative to those

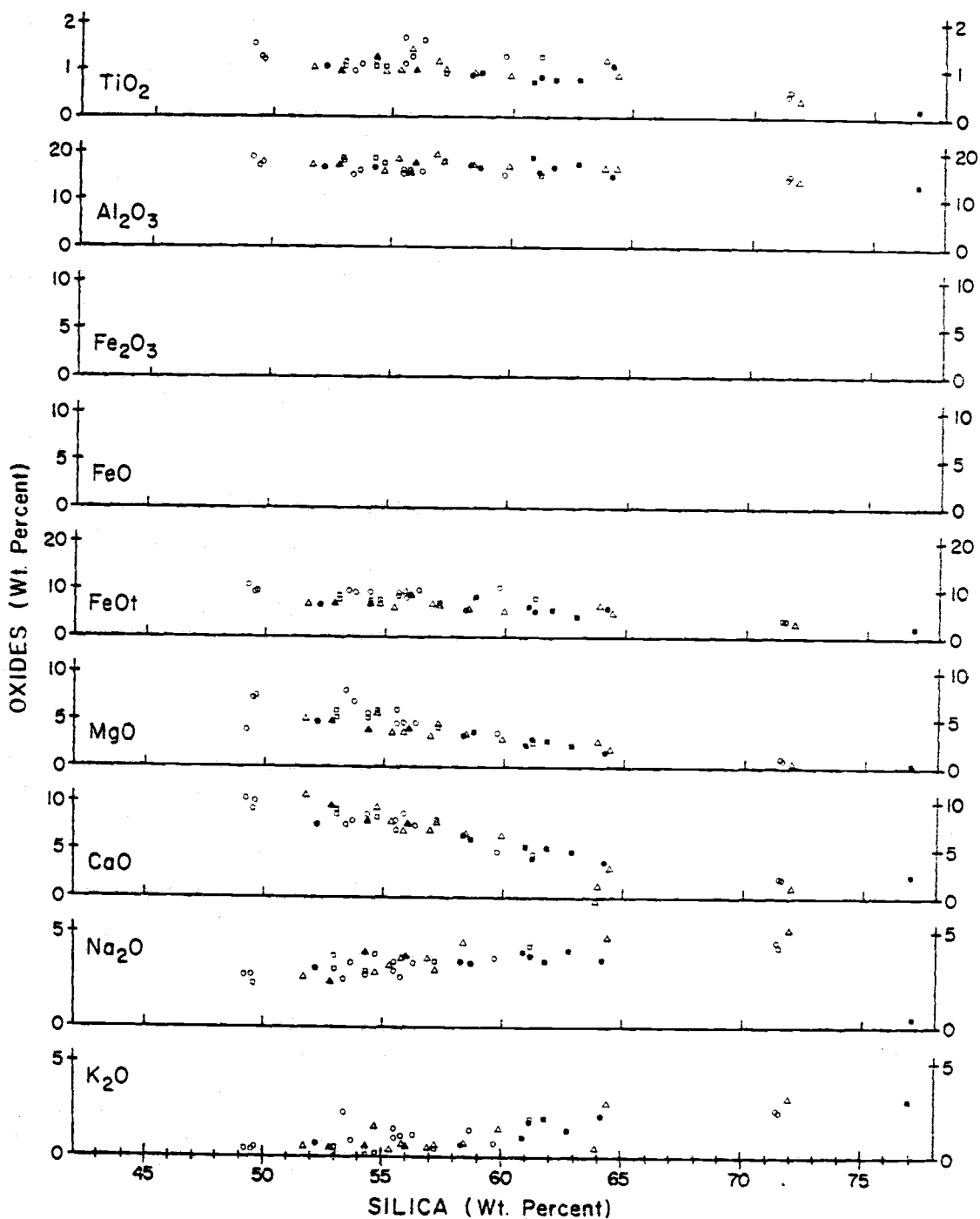


Figure 3. Harker variation diagram of major oxide components in volcanic rocks of the Western Cascades (analytical data are listed in Appendix 2; total iron as  $\text{FeO}_t$ ; symbols for mining districts defined in Figure 4).

from other districts. In general, samples of volcanic rocks from the northern districts (Washougal, North Santiam, Detroit Dam, and Quartzville) have lower contents of  $\text{FeO}_t$ ,  $\text{TiO}_2$ , and  $\text{MgO}$  than do those from the Blue River and Bohemia districts. The chemical distinction between volcanics of the Bohemia district and those of the other districts is clearly illustrated by a plot of  $\text{FeO}_t$  versus  $\text{MgO}$  as given in Figure 4. This diagram documents the higher values for  $\text{FeO}_t$  and  $\text{MgO}$  in rocks of the Bohemia district. Data for few of these districts show the simple calc-alkaline trend displayed by the average Quaternary volcanic rocks of the High Cascades (White and McBirney, 1978).

The ternary AFM diagram ( $\text{K}_2\text{O} + \text{Na}_2\text{O} - \text{FeO}_t - \text{MgO}$ ) given in Figure 5 demonstrates the tholeiitic character of some samples from the Bohemia district. Samples of volcanic rock from all other districts plot within the calc-alkaline field. The NKC ternary diagram ( $\text{Na}_2\text{O} - \text{K}_2\text{O} - \text{CaO}$ ) portrayed in Figure 6 indicates that these volcanic rocks are slightly more deficient in  $\text{K}_2\text{O}$  than is common for continental calc-alkaline suites. The anomalous depletion of  $\text{Na}_2\text{O}$  in a sample of "quartz latite" from the North Santiam district is attributable to an assemblage of quartz and sericite formed by hydrothermal alteration.

In summary, the flow rocks of these mineralized areas are predominantly basalts, basaltic andesites, and andesites. Most are porphyritic with plagioclase feldspar and augite as the most common phenocrysts. They contain more  $\text{CaO}$  and less  $\text{K}_2\text{O}$  than most continental calc-alkaline suites. Samples from the Bohemia and Blue River

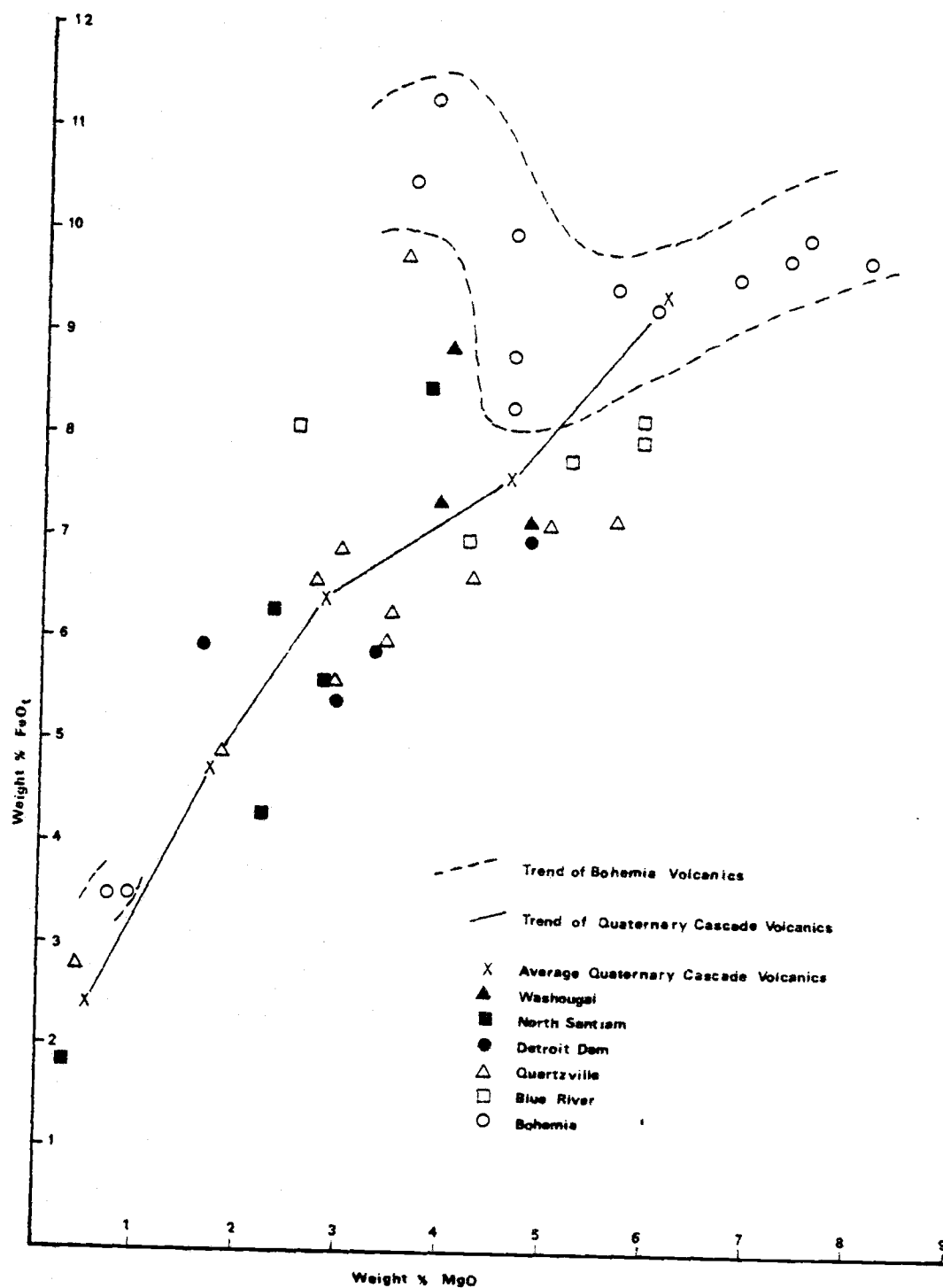


Figure 4. Distribution of MgO versus  $\text{FeO}_t$  in volcanic rocks of the Western Cascades (trend for average Quaternary Cascade volcanics from White and McBirney, 1978).

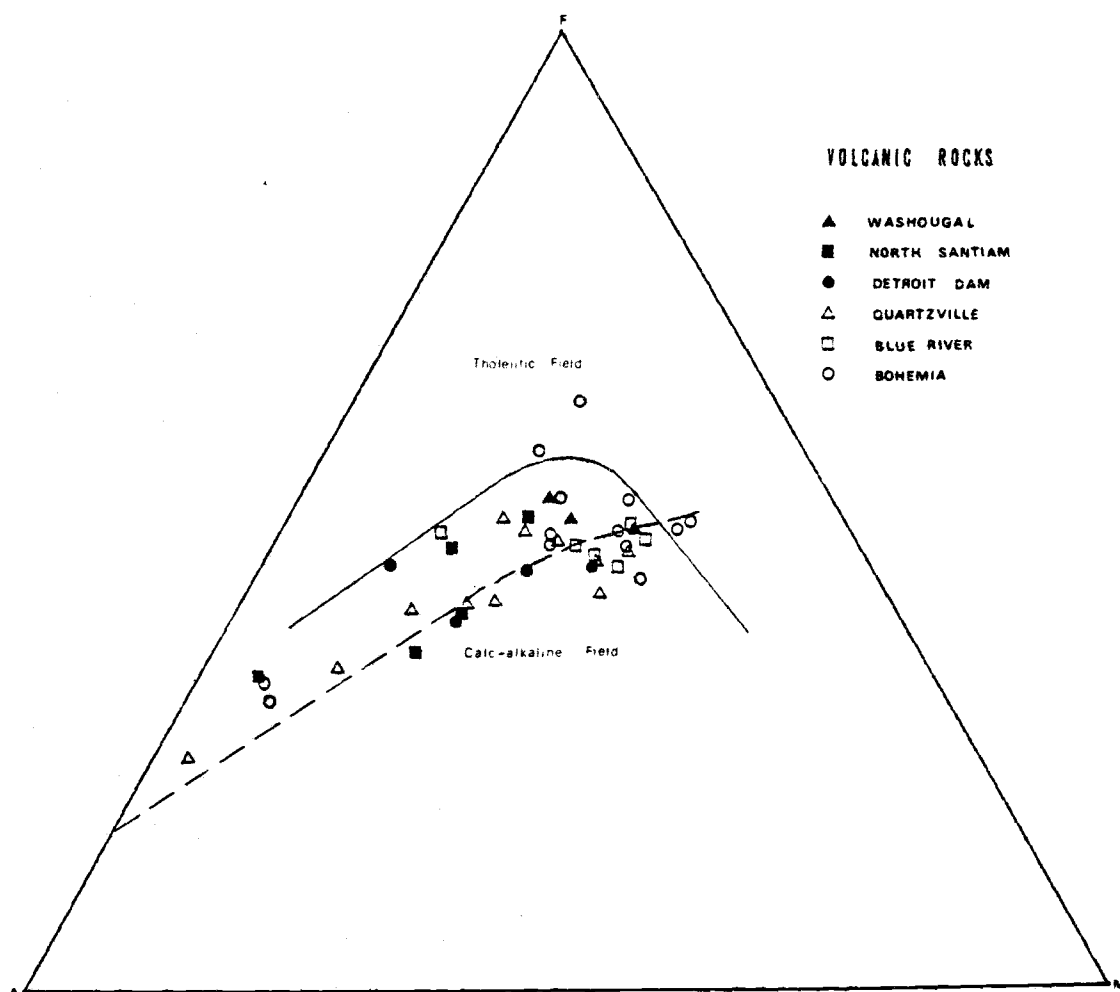


Figure 5. AFM diagram for volcanic rocks of the Western Cascades (A =  $\text{Na}_2\text{O} + \text{K}_2\text{O}$ , F =  $\text{FeO}_t$ , M =  $\text{MgO}$ ; dashed line is trend for recent Cascade volcanics after Carmichael, 1964, and solid line separates tholeiitic and calc-alkaline fields of Irvine and Baragar, 1971).

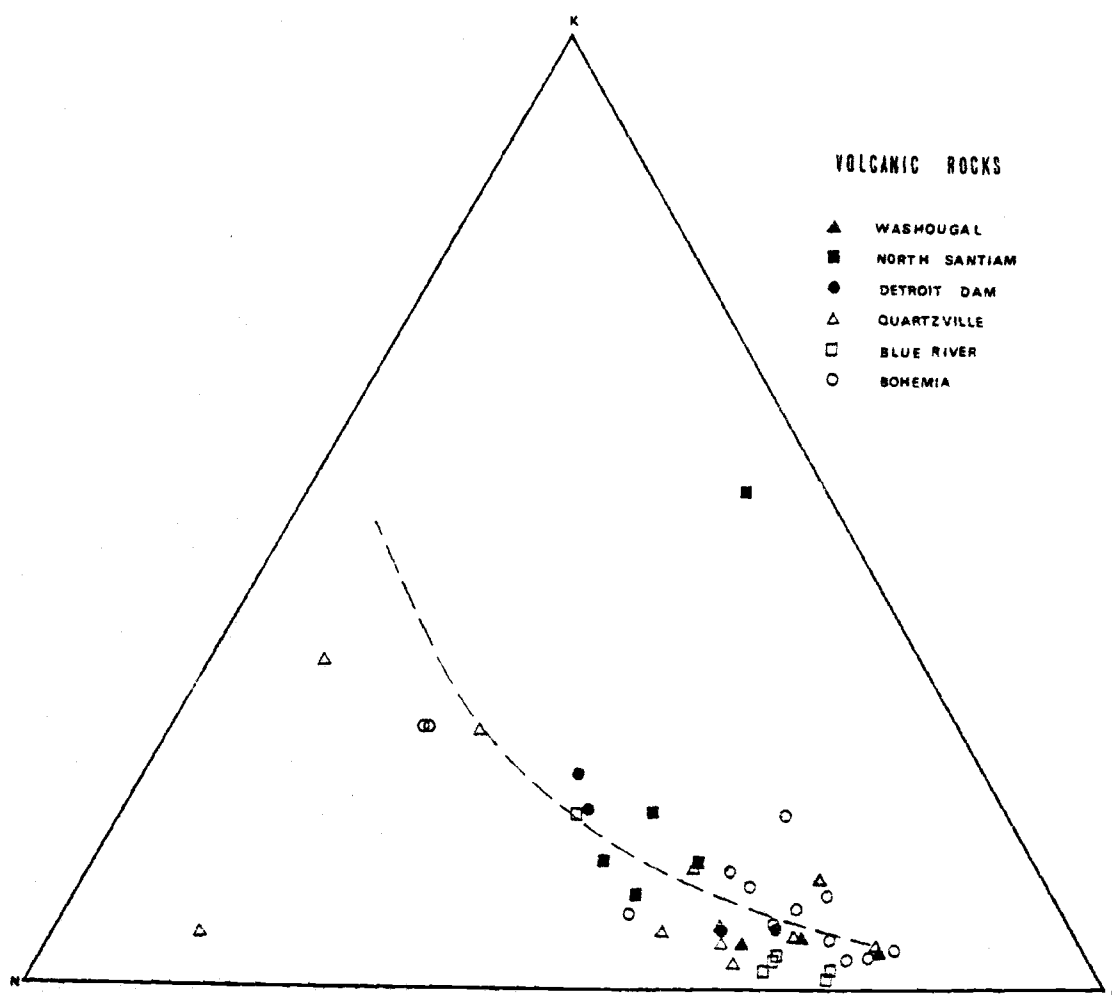


Figure 6. NKC diagram for volcanic rocks of the Western Cascades ( $N = \text{Na}_2\text{O}$ ,  $K = \text{K}_2\text{O}$ ,  $C = \text{CaO}$ ; dashed line is trend for recent Cascade volcanics after Carmichael, 1964).

districts have higher contents of  $\text{FeO}_t$ ,  $\text{MgO}$ , and  $\text{TiO}_2$  than do those from districts to the north. Flows of the Bohemia district display some enrichment of total iron, and several of these samples plot within the tholeiitic field of Irvine and Baragar (1971).

### Age and Correlation

Neither radiometric nor paleontologic ages are available for the volcanic host rocks in mineralized areas of the Western Cascades. Sutter (1978) reported K-Ar age determinations for rocks collected near the North Santiam-Detroit Dam area and the Blue River district. Volcanic rocks of the Blue River, North Santiam, Detroit Dam, and Quartzville areas can be correlated with the Sardine volcanic episode (14 to 17 m.y.) on the basis of these dates, the relative stratigraphic positions of samples dated, and formational descriptions of Peck and others (1964). Some of the rocks from the North Santiam area give younger Miocene dates (11 to 12 m.y.), which indicate that two periods of volcanism may be represented in the district. The Detroit pluton (7 m.y.) is probably related to this later period of volcanism. Schaub (1978) tentatively correlated volcanic rocks of the Bohemia district with the Little Butte Volcanic Series on the basis of formational descriptions. The relative stratigraphic position of these volcanic rocks to those dated by Sutter (1978) is uncertain. Volcanic rocks of the Bohemia district exhibit a moderate tholeiitic trend of iron enrichment similar to one shown by White and McBirney (1978) for rocks of Little Butte age from the North Santiam

area. Schriener (1978) has tentatively correlated the volcanic rocks of the Washougal district with those of the Ohanapeocosh formation (Eocene to Oligocene).

## PLUTONIC ROCKS

Intrusions of intermediate composition are closely associated with mineralization in the Western Cascades. They range in size from small dikes a few centimeters wide to stocks several kilometers in width. The larger plutons include the Silver Star stock in the Washougal district, the Detroit stock on the North Santiam River, a granitic stock in the Middle Santiam River, the Nimrod stock on the McKenzie River, and the Champion (Bohemia) stock in the Bohemia district. Smaller plutons are found in all districts and are associated with propylitic alteration in the Still Creek-Laurel Hill areas near Mt. Hood, at Shellrock Mountain, Oregon, near the Columbia River, and in the Wind River/Wind Mountain (Wise, 1970) area in Washington. Contacts of smaller plutons with their country rocks are usually sharp and steep and they often have narrow chilled margins and abundant xenoliths of the adjacent country rock. The larger plutons are sometimes flat-topped and contacts may be obscured by hydrothermal alteration of the pluton and surrounding country rock. Breccias are common near the contacts of some intrusions (Munts, 1978; Pungrassami, 1970). A variety of intermediate to silicic rock types are represented by these plutons. Quartz diorites and granodiorites are most common, but diorites, tonalites, and quartz monzonites are also present in many districts. Granite is found in the Nimrod stock (Buddington and Callahan, 1936), the Middle Santiam stock (Munts, 1978), and as granitic aplites in the Washougal,

Quartsville, and Bohemia districts. The color of the intrusions ranges from light gray to dark gray on fresh surfaces. Aplites and granitic intrusions may be white to pinkish gray in color.

Most of the rocks are porphyritic with white phenocrysts of plagioclase feldspar ranging in size from one to seven millimeters in length. Augite, hornblende, and hypersthene are also common phenocrysts, whereas quartz is rarely present as phenocrysts. The ground-mass of most smaller plutons is aphanitic to finely crystalline in texture. Larger plutons tend to have more coarsely crystalline textures (although crystals are rarely larger than two millimeters in diameter) and they are commonly equigranular. Very fine-grained equigranular rocks are found in the North Santiam district (the Ruth diorite of Olson, 1978).

Most plutons are easy to distinguish in the field by their intrusive contacts, large cloudy phenocrysts of plagioclase feldspar, and intermediate gray colors. The larger plutons can be distinguished from flow rocks by their equigranular textures, although contacts may be obscured by hydrothermal alteration.

### Petrography

Plutonic rocks of the Western Cascades are remarkably uniform petrographically, although there are some textural and mineralogical variations. In some districts, the exposed plutons are small and textural and mineralogical variations apparently are independent of chemical composition, which renders the identification and

classification of distinct intrusive phases difficult. The Blue River district has perhaps the best examples of such plutons, with textures ranging from glassy to fine-grained hypidiomorphic granular in rocks with essentially the same chemistry and similar mineralogy. In the Bohemia district, Schaub (1978, p. 41) has noted that rocks which were "distinguished modally as quartz diorite, granodiorite, and quartz monzonite were essentially chemically identical." In contrast, Schriener (1978) and Shepard (1979) have reported that plutonic phases of the Washougal district can be distinguished on the basis of texture, mineralogy, and chemistry as is possible in the more deeply eroded parts of stocks and batholiths. Nevertheless, many of these plutonic phases show variations in texture and chemistry.

Almost all of the intermediate plutonic rocks in these mineralized areas are porphyritic, although some of the larger plutons have equigranular phases. Groundmass textures range from hyalopilitic in a few small intrusions in the Blue River and Quartzville districts to fine- and medium-grained hypidiomorphic granular and seriate. Coarsely crystalline varieties are rare. Micrographic textures, and less commonly, myrmekitic textures are found in some of the coarser grained plutons. A few of the plutons contain miarolitic cavities or vesicles (Shepard, 1979; Storch, 1978). However, the primary textures and mineralogy of these intrusions are commonly obscured by alteration.

As was previously noted for the textural variations, mineralogical variations of the plutonic rocks between districts are principally a function of the size of exposed plutons. In districts characterized by small plutons, mineralogy is remarkably similar even between samples with greatly differing chemical composition. The plutons of the Blue River district have essentially similar modal analyses, yet they may vary by several weight percent for some of the major oxide constituents. This relationship is probably the result of rapid crystallization, which results in the formation of metastable minerals; particularly in variable compositions of feldspars and mafic minerals. Thus, modal abundances for some plutons, such as those of the Bohemia district, are seemingly independent of their major oxide chemistry. In districts having larger plutons, such as the Washougal and North Santiam districts, mineralogy and chemistry are more closely correlative. There also is a correspondingly greater mineralogical variation between plutonic phases of differing chemistry and relative age.

The common magmatic minerals of these plutons include plagioclase feldspar, pyroxene, hornblende, quartz, biotite, and potassium feldspar. Accessory minerals include apatite, zircon, sphene, and iron-titanium oxides. The magmatic minerals are usually altered to an assemblage which may include the following hydrothermal minerals: albite, chlorite, epidote, carbonate, white mica, biotite, potassium feldspar, and clays. Hydrothermal alteration, in combination with

the original finely crystalline textures, precludes an accurate determination of the original mineralogy of many of these rocks.

Quartz is a common constituent of plutonic rocks of the Western Cascades, although it does not usually occur in large quantities. It is most abundant in aplites where it may comprise up to 43 percent of the rock. In other plutonic phases, quartz may be present in amounts up to 30 percent, although less than one-third of the samples examined contained more than 20 percent quartz. This mineral usually occurs interstitially or as micrographic intergrowths with feldspars, although it also may be present as phenocrysts. Quartz is also present as an alteration product which may be difficult to distinguish from primary magmatic quartz.

Potassium feldspar is not an abundant constituent of plutons of the Western Cascades. It was observed in less than one-half of all plutonic rocks examined, where its occurrence was either as an interstitial component, or as micrographic intergrowths with quartz. Although it rarely comprises more than 20 percent of the plutons, this feldspar may constitute up to 40 percent of the aplites. In spite of the fact that potassium feldspar is a rare minor component in the small plutons of the Blue River district, chemical analyses indicate that they contain up to 20 percent normative orthoclase, which suggests that the  $K_2O$  may be contained in the plagioclase feldspar and in the fine-grained groundmass.

Plagioclase feldspar is the most abundant primary phase and is contained in both the phenocrysts and groundmass of most plutonic

rocks from the Western Cascades. It is most commonly andesine in composition, although labradorite is found in chilled phases and mafic lithologies, and oligoclase is common in the most silicic rocks. Plagioclase feldspar comprises 40 to 60 percent of most intrusions, but varies with rock types from 10 percent in aplites to 79 percent in diorites. This feldspar varies with respect to both anorthite content and compositional homogeneity in different plutons. The plagioclase feldspar of most plutons exhibits normal or oscillatory zonations. However, the feldspar of some larger intrusions is not zoned, which indicates that it may have crystallized more slowly under conditions of equilibrium.

Pyroxenes and hornblende are the most common ferromagnesian minerals in plutons from the Western Cascades. Augite is the most abundant pyroxene although its positive identification may be difficult because of alteration. It is common as phenocrysts in most of the porphyritic phases. Hypersthene also is present as phenocrysts, but it is relatively uncommon. Hornblende is second to augite in abundance as the predominant ferromagnesian mineral. It occurs as phenocrysts, but is rarely found in small plutons. Biotite is relatively rare and its occurrence is almost exclusively restricted to large equigranular plutons. It is not present in any of the small plutons of the Blue River district. Muscovite is present only in granitic aplites from the Washougal and Quartzville districts.

Accessory minerals include apatite, sphene, iron-titanium

oxides, and zircon. These minerals are usually very fine-grained and may be difficult to identify because of alteration.

Alteration of the plutonic rocks of the Western Cascades is ubiquitous. Ferromagnesian minerals are commonly altered to chlorite, epidote, clays, carbonate, actinolite, urallite, and biotite. Epidote, carbonate, albite, white mica, clays, and rarely potassium feldspar replace plagioclase feldspar, whereas potassium feldspar may be altered to clays and white mica. Alteration in many rocks is so extensive that accurate estimates (and sometimes identification) of the primary modal minerals is impossible.

A ternary diagram showing the modal abundances of feldspars and quartz is presented in Figure 7. Using the IUGS classification (Streckeisen, 1973) of plutonic rocks, most of those from the Western Cascades may be classified as quartz diorites and granodiorites. Granites, tonalites, diorites, and quartz monzodiorites are less common. The single sample of alkali-feldspar granite is of aplite from the Washougal district (Shepard, 1979).

### Petrochemistry

Chemical analyses of 34 samples of plutonic rocks from the Western Cascades are presented in Appendix 3. Many of these analyses were recorded in theses by Pungrassami (1970), Muntz (1973), Ness (1978), Olson (1978), Schaub (1973), Schriener (1978), Storch (1978), and Shepard (1979). In addition, the data include previously unreported analyses for samples from the Detroit Dam and other areas,

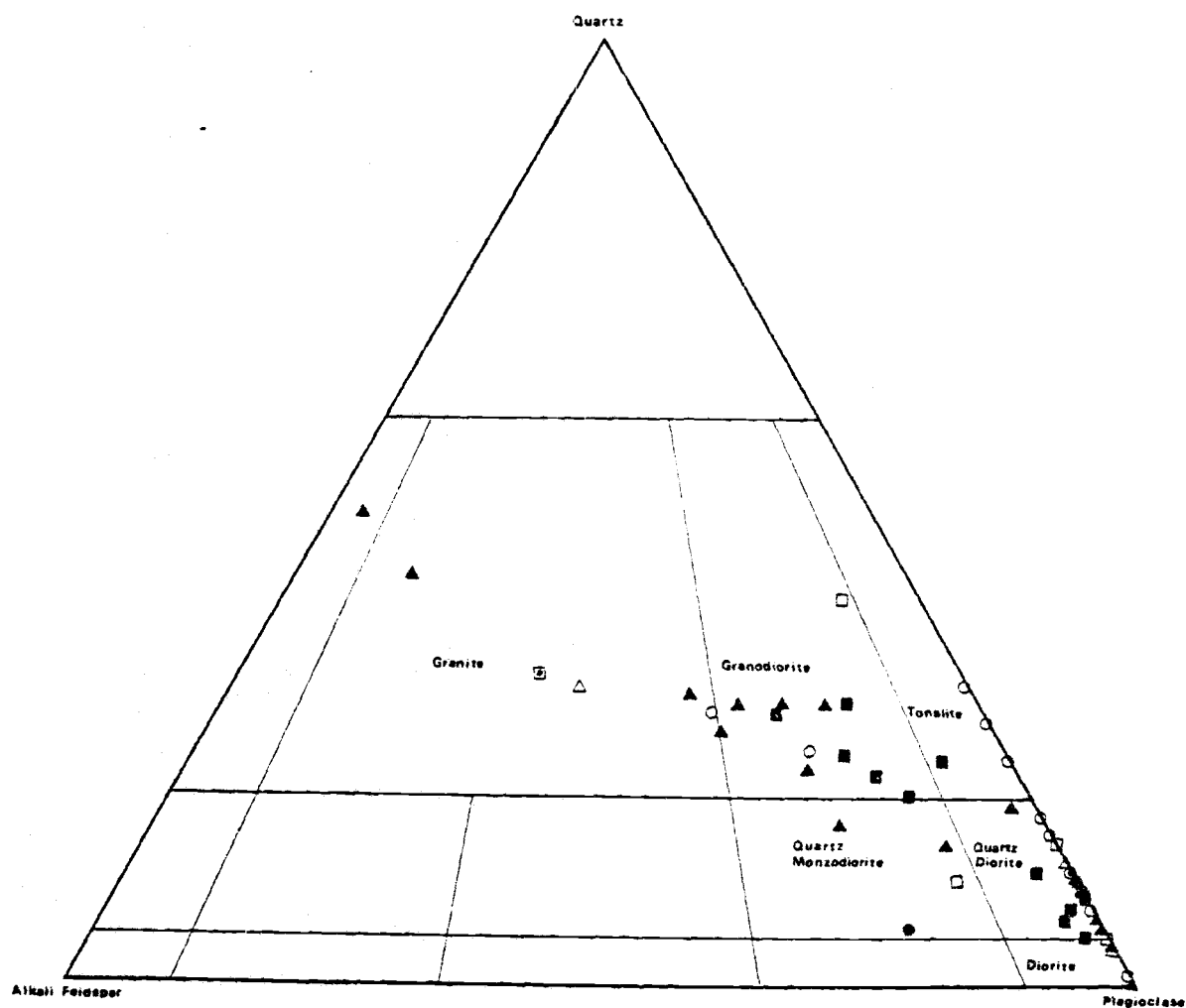


Figure 7. Ternary distributions of modal quartz, alkali feldspar, and plagioclase feldspar in plutonic rocks of the Western Cascades.

and the reanalysis of two samples from the Washougal district. These analyses document a relatively broad compositional range for the plutons of the Western Cascades. Sample distribution, as was the case for the volcanic rocks, may be slightly biased in that the late-stage granitic phases (aplites and silicic dikes), which are volumetrically insignificant, constitute about six percent of the plutonic rocks analyzed. However, this bias is partly offset by a single sample representing the relatively large and granitic Nimrod stock.

Chemical trends shown by the plutonic rocks are similar to those of the volcanic rocks of the region. The principal difference is that most of the volcanic rocks have lower contents of  $\text{SiO}_2$  than the majority of the plutonic rocks. Storch (1978) speculated that the plutons of the Blue River district represented the "last magmatic activity of a dying volcanic center" as indicated by their greater chemical differentiation relative to the more mafic volcanic rocks, and by the relative ages of volcanic and plutonic units. Such simple relationships do not exist in other districts, although most workers speculate that the volcanic and plutonic rocks are genetically related. Because silicic magmas have higher viscosities and lower crystallization temperatures than their mafic counterparts, other factors being equal, they are more likely to solidify at depth as plutons than at the surface as volcanics; especially if an aqueous hydrothermal phase is expelled during ascent of the magma.

Chemical data for plutonic rocks of the Western Cascades follow more closely the simple calc-alkaline trend than do those for the volcanic rocks. However, the alkali-lime index for the plutonic rocks is between 60 and 64, which is somewhat more calcic than the range of 56 to 61 for calc-alkaline suites (Peacock, 1931). Chemical trends as shown on the Harker variation diagram in Figure 8 are typical of calc-alkaline suites and exhibit remarkably little spread for samples collected from such a larger geographic area. The components  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{TiO}_2$ ,  $\text{CaO}$ , and  $\text{Al}_2\text{O}_3$  decrease with increasing  $\text{SiO}_2$ , whereas  $\text{K}_2\text{O}$  increases.  $\text{Na}_2\text{O}$  shows no obvious relationship to  $\text{SiO}_2$  content. As previously noted for the volcanic rocks, the plutonic rocks of the Bohemia and Blue River districts have slightly higher contents of  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2$ , and  $\text{MgO}$  at a given content of  $\text{SiO}_2$  than do samples from the other districts. However, the contents of  $\text{FeO}_t$  versus  $\text{MgO}$  for plutonic rocks as plotted in Figure 9 do not exhibit the markedly higher values that are typical of their volcanic counterparts (Figure 4).

Compositions of the plutonic rocks plotted on the ternary AFM diagram of Figure 10 show a moderate trend of alkali enrichment relative to total iron and magnesia. This distribution closely approximates other calc-alkaline trends as described by Nockolds and Allen (1953) and Carmichael (1964). Moreover, compositions of these plutons, excluding three samples from the Blue River and Quartzville districts, plot as a calc-alkaline trend on the ternary NKC diagram given by Figure 11. Similar trends have been obtained for igneous

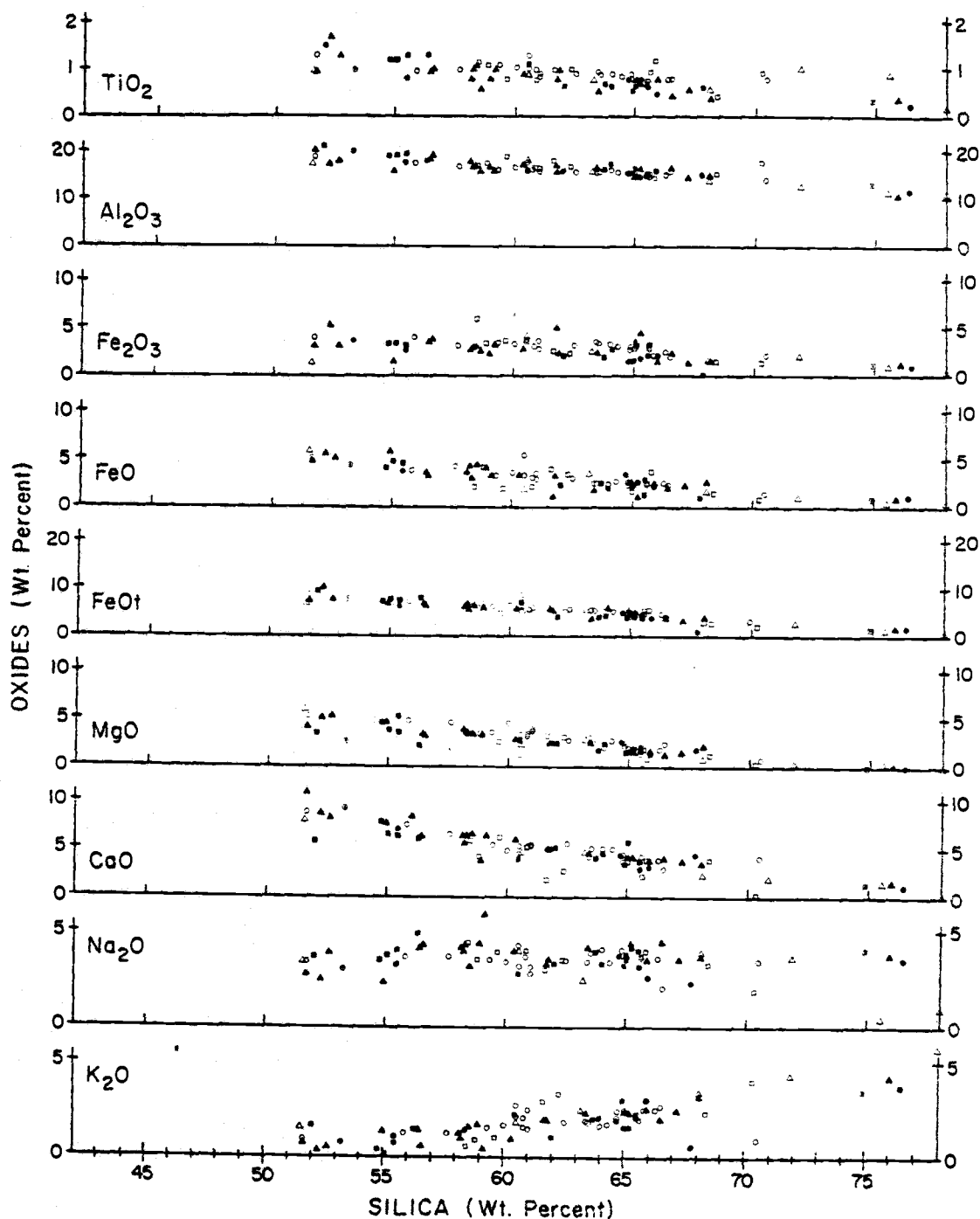


Figure 8. Harker variation diagram of major oxide components in plutonic rocks of the Western Cascades (analytical data are listed in Appendix 3; total iron as FeOt; symbols for plutons and mining districts defined in Figure 10).

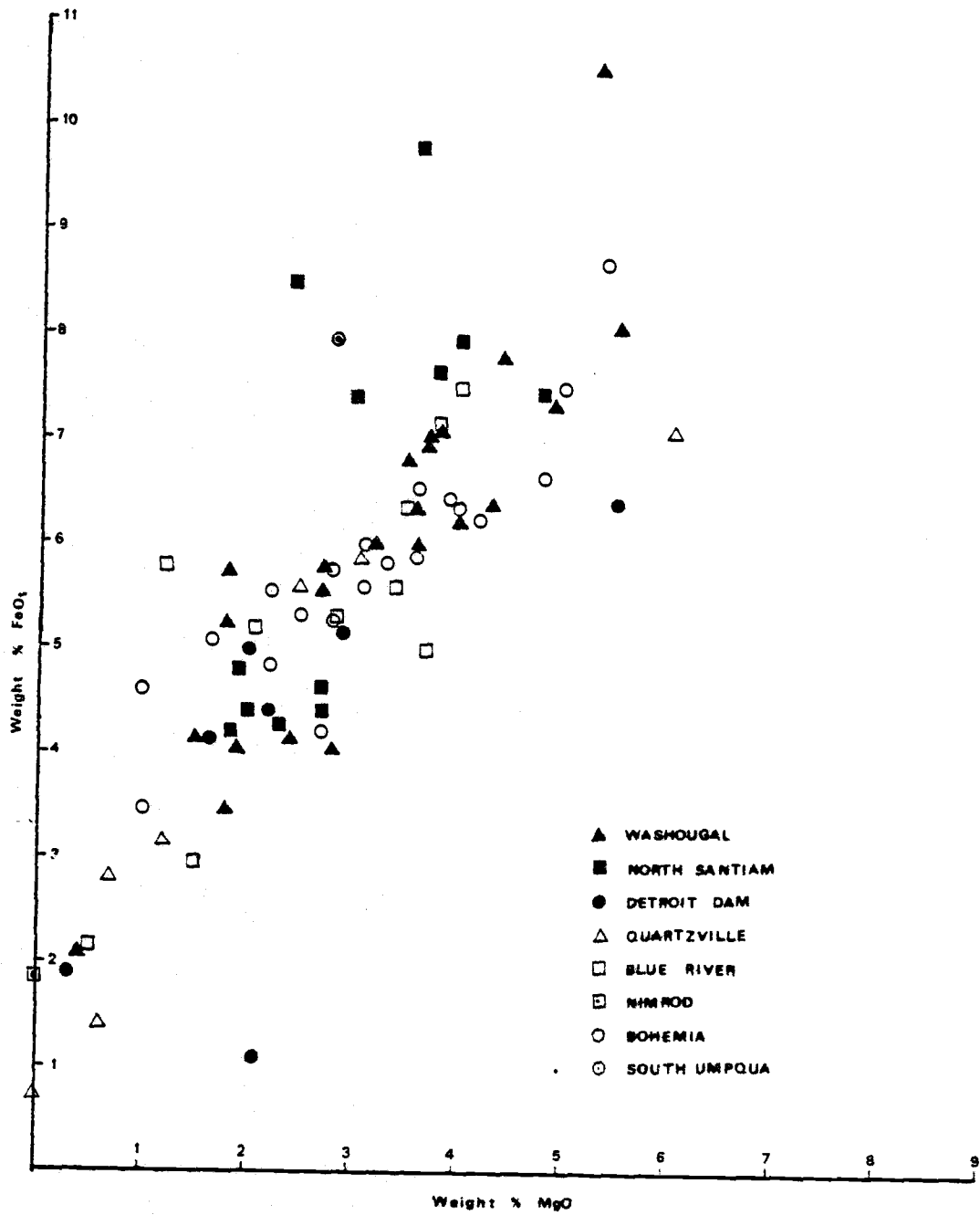


Figure 9. Distribution of MgO versus  $\text{FeO}_t$  in plutonic rocks of the Western Cascades.

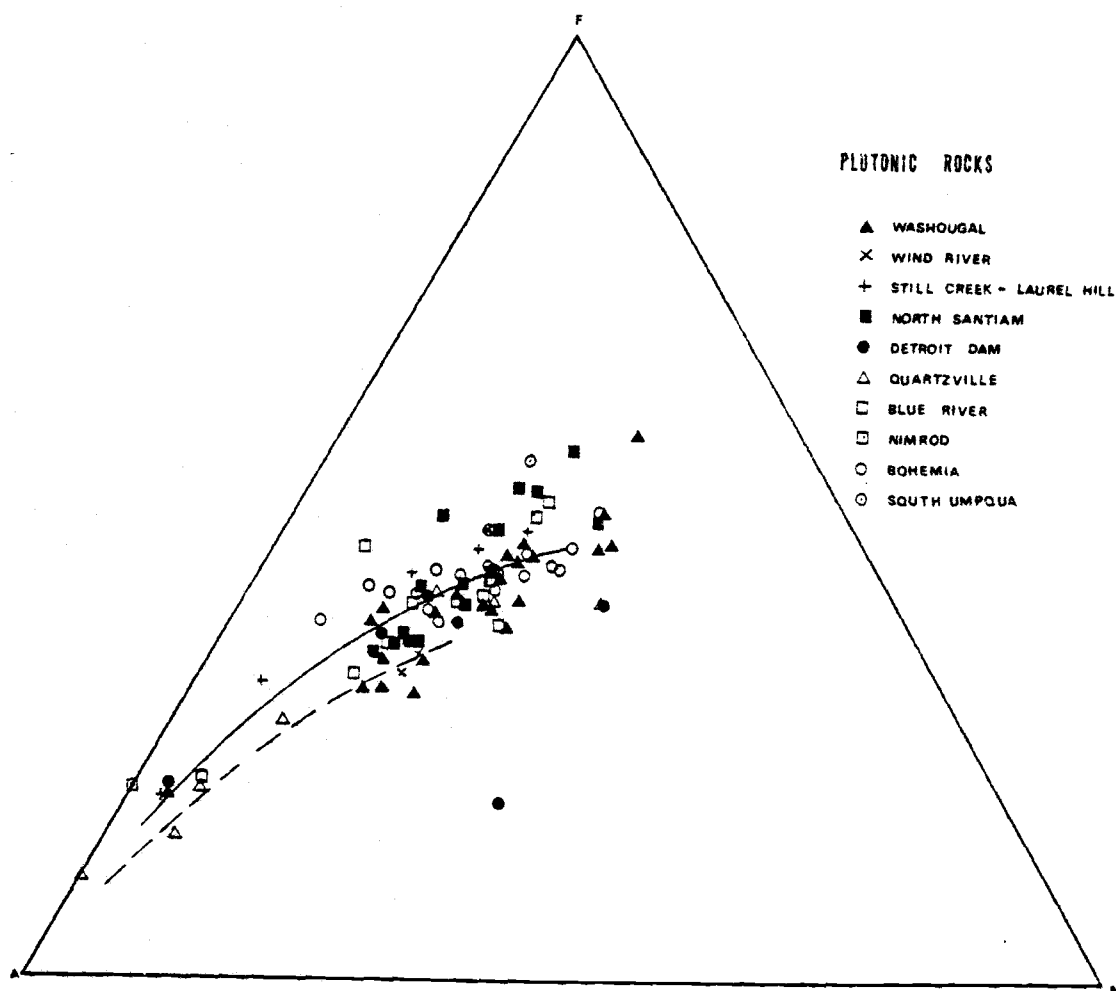


Figure 10. AFM diagram for plutonic rocks of the Western Cascades ( $A = \text{Na}_2\text{O} + \text{K}_2\text{O}$ ,  $F = \text{FeO}_t$ ,  $M = \text{MgO}$ ; solid line is the calc-alkaline trend after Nockolds and Allen, 1953, and dashed line is the trondhjemite trend after Larsen and Poldervaart, 1961).

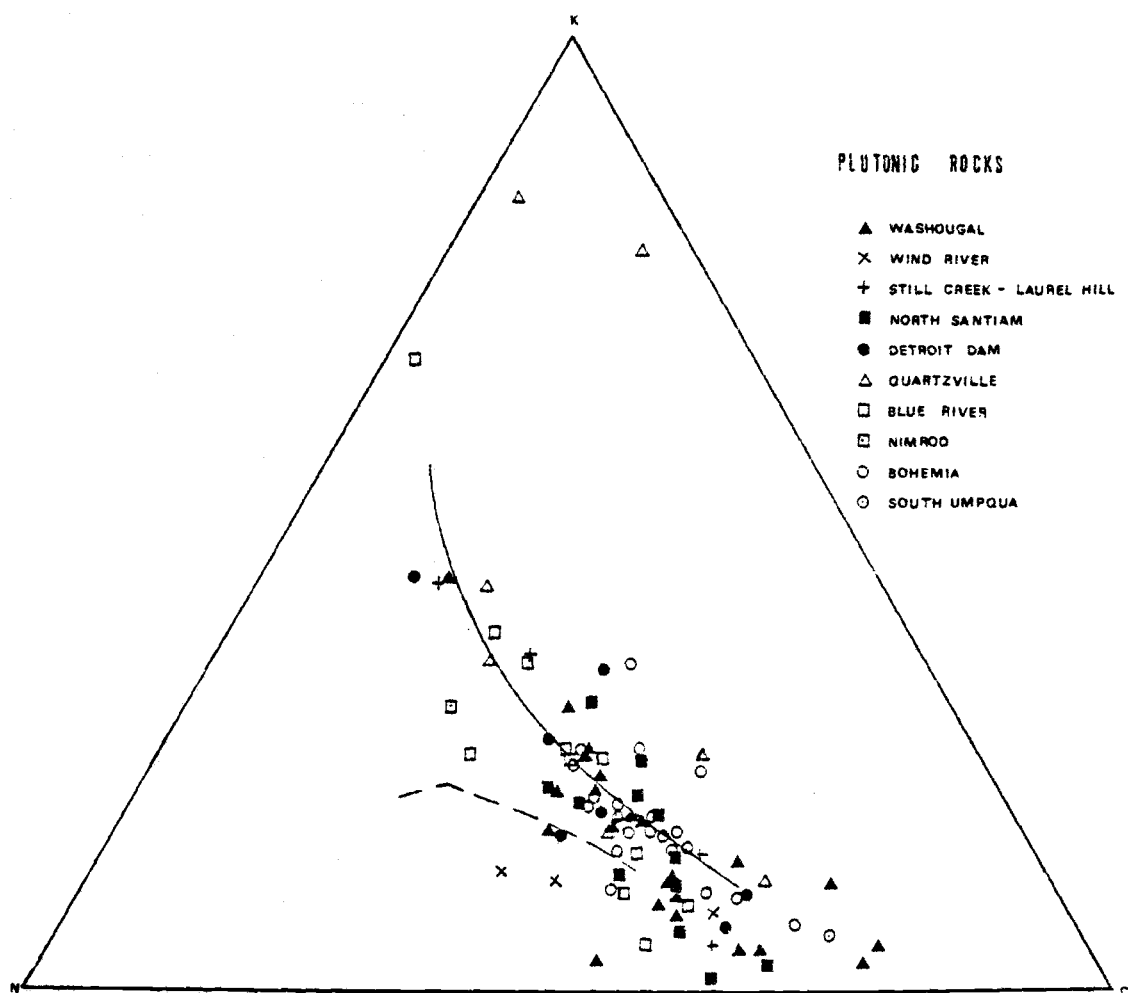


Figure 11. NKC diagram for plutonic rocks of the Western Cascades (N =  $\text{Na}_2\text{O}$ , K =  $\text{K}_2\text{O}$ , C =  $\text{CaO}$ ; solid line is the calc-alkaline trend after Nockolds and Allen, 1953, and dashed line is the trondhjemite trend after Larsen and Poldervaart, 1961).

rock suites from the Cascade volcanics and Southern California batholith (Nockolds and Allen, 1953) and porphyry associated plutons in island arcs of the southwestern Pacific and the Caribbean (Titley and Beane, 1981). However, the compositional data for pluton of the Western Cascades do not demonstrate the distinct trondhjemitic trend ( $\text{Na}_2\text{O}$  enrichment) as shown by some older intrusions of the Pacific Northwest including the Bald Rock (Larsen and Poldervaart, 1961) and Guichon Creek (Field and others, 1975) batholiths.

The frequency distribution of  $\text{K}_2\text{O}$  in samples of plutonic rock from the Western Cascades and those of equivalent samples from island arc and other continental environments are illustrated in Figure 12. Comparisons of these distributions indicate that the majority of Cascade plutonic rocks are deficient in  $\text{K}_2\text{O}$  relative to plutons associated with porphyry-type deposits of the southwestern U.S., but they are slightly enriched in  $\text{K}_2\text{O}$  relative to mineralized island arc plutons of the Caribbean, according to the data of Kesler and others (1975). Compositional domains portrayed on the potash versus silica diagram of Figure 13 show that the plutons of the Western Cascades more closely resemble those from island arc terrains such as the Caribbean and south central British Columbia than the continental plutons of Bingham, Utah, and southern Arizona (see Kesler and others, 1975; Creasey, 1977; and Briskey and others, 1981). This resemblance to plutons of island arc terranes is verified on an alkali-silica diagram of Figure 14. Titley and Beane (1981) found that intrusive rocks from island arcs could be distinguished from

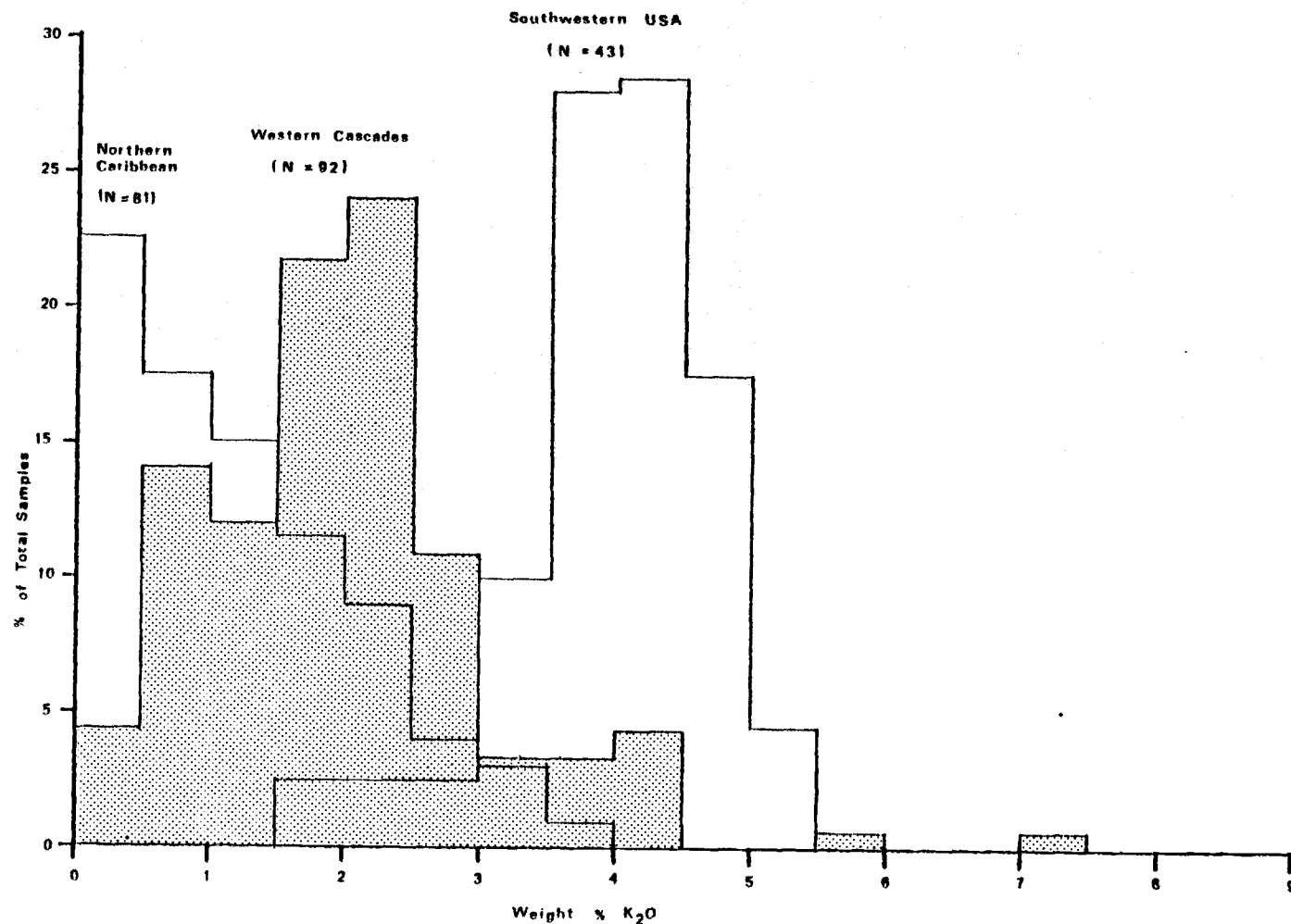


Figure 12. Frequency distribution of K<sub>2</sub>O in plutonic rocks of the Western Cascades and in those of the northern Caribbean and southwestern U.S. (modified from Kesler and others, 1975).

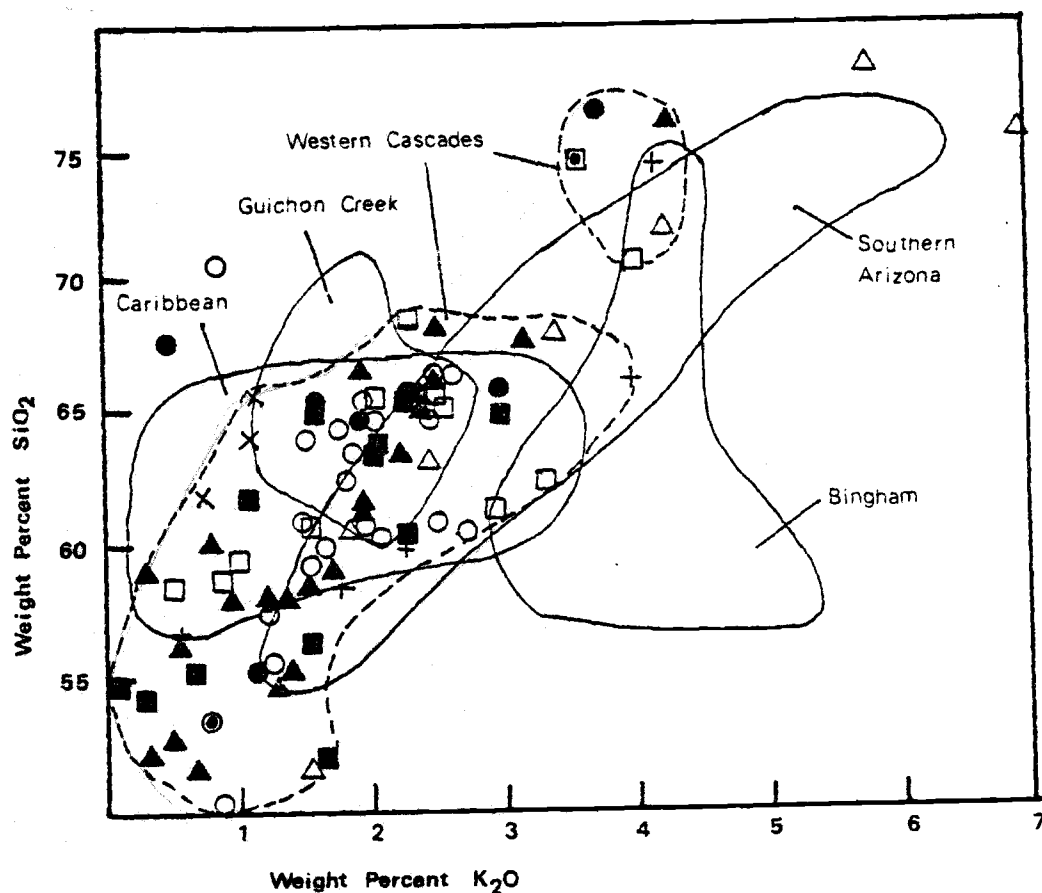


Figure 13. Distribution of  $K_2O$  versus  $SiO_2$  in plutonic rocks of the Western Cascades and in those of the northern Caribbean, Guichon Creek batholith, southern Arizona, and Bingham District, Utah (modified from Kesler and others, 1975; Creasey, 1977, and Briskey and others, 1981).

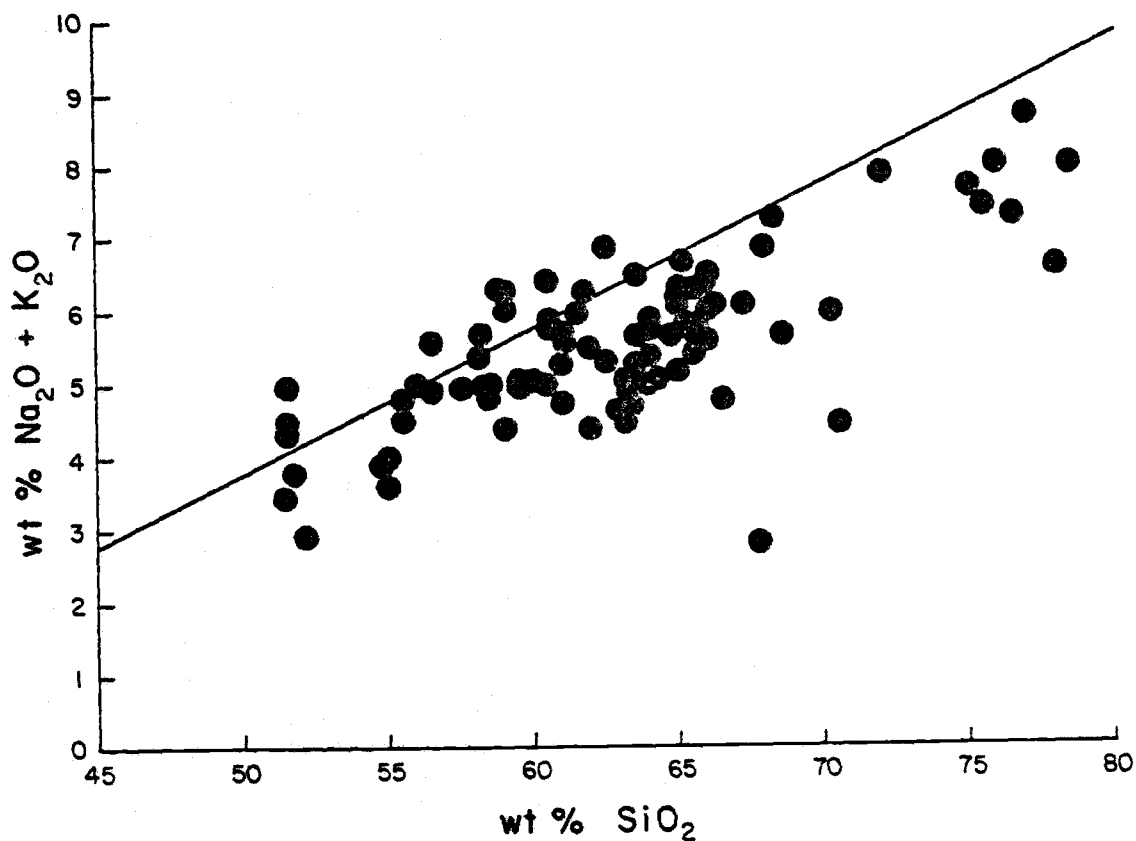


Figure 14. Alkali-silica variation diagram of intrusive rocks of the Western Cascades. Most samples from cratonic suites plot above the line whereas most plutons from island arc terranes plot below the line.

cratonic suites at continental edges and from alkaline suites, although there is some overlap between the cratonic and island arc rocks. Plotted in this way, plutons from the Western Cascades are essentially indistinguishable from the island arc suites of the Caribbean, the southwestern Pacific, and Canada.

Normative mineral abundances have been calculated from the chemical data for plutonic rocks and both are listed in Appendix 3. The calculations were undertaken to obviate problems caused by the finely crystalline textures and discrepancies between the chemistry and modal mineralogy of some samples. The normative mineralogy facilitates comparisons to the more coarsely crystalline samples of deep-seated intrusions and may reveal differences that are not readily apparent from visual inspection of the chemical data (such manipulations, however, may also generate false differences).

The relative deficiency of  $K_2O$  in plutonic rocks of the Western Cascades as previously noted (see Figures 12 and 13) is further demonstrated by distributions of normative quartz, orthoclase, and plagioclase feldspar (albite + anorthite) given in Figure 15. Nonetheless, samples from the various districts do plot in a narrow band from diorite, through quartz diorite and quartz monzodiorite, to granodiorite. A comparison of the normative abundances of quartz and feldspars to the modal abundances of these minerals (see Figure 7) indicates that modal orthoclase is much less common than its normative equivalent. This is consistent with the data for the Blue River district (Storch, 1978) which showed that plutons with very little

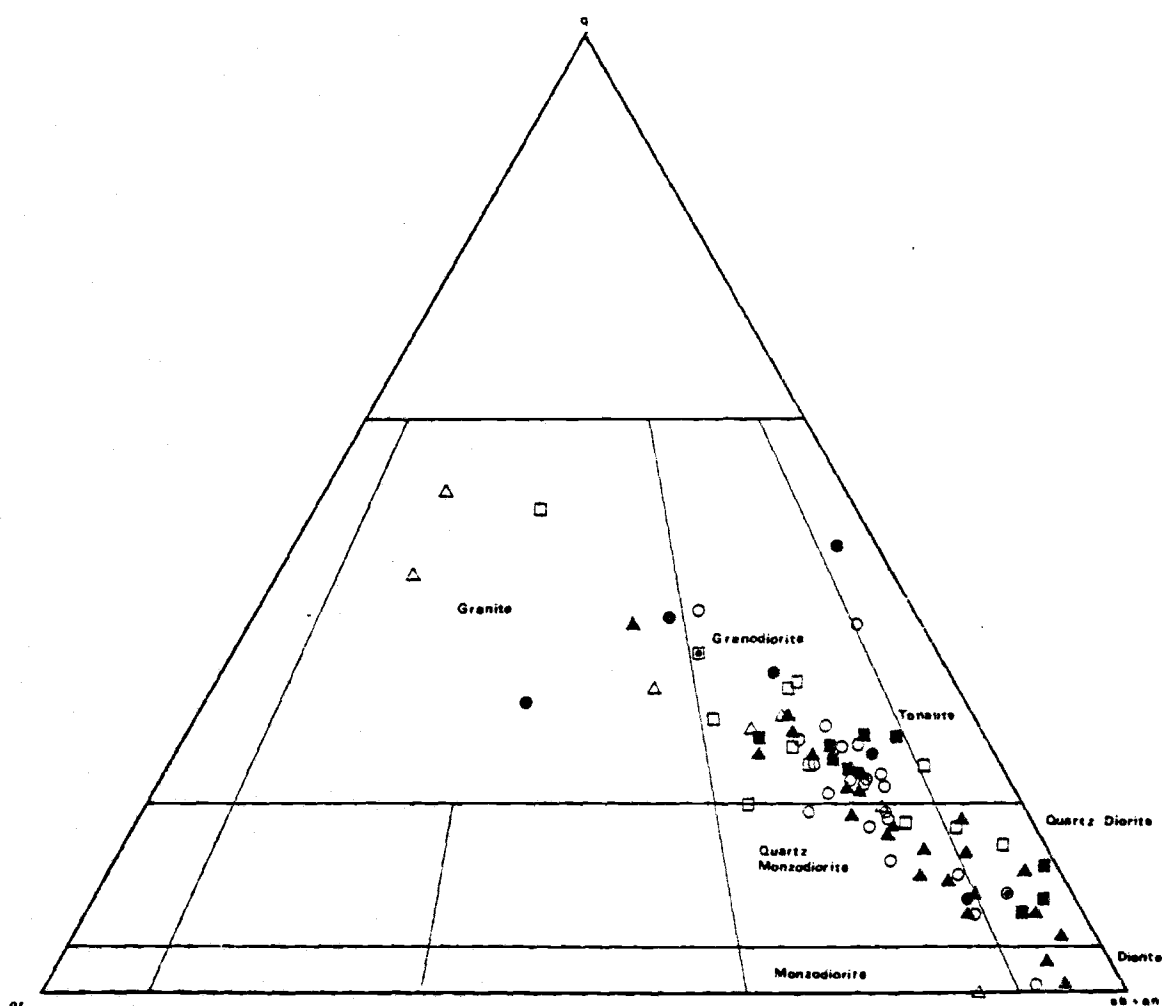


Figure 15. Ternary distributions of normative quartz, orthoclase, and plagioclase (albite + anorthite) in plutonic rocks of the Western Cascades.

modal potassium feldspar contained as much as 20 percent normative orthoclase. Discrepancies between modal and normative feldspar abundances are not usually observed in studies of the more deep-seated plutons such as the Cloudy Pass batholith, as described by Cater (1969).

Normative corundum, an indicator of oversaturation in  $Al_2O_3$ , is present in 30 percent of the samples and generally constitutes less than two percent of the normative minerals. One-half of the samples containing more than two percent normative corundum are from plutons of the Blue River district, whereas few are from those of the Bohemia and Washougal districts. The smaller sizes and more finely crystalline textures of plutons from the Blue River district indicate a shallower level of emplacement, which in turn suggests a relationship between depth of emplacement and the extent of alumina saturation. However, the large stock of the Detroit Dam area also has several normative corundum-rich samples, although size and textures indicate that it was emplaced at a relatively deep level. Saturation with respect to  $Al_2O_3$  may also be related to the age of pluton emplacement, as intrusions of the Bohemia and Washougal districts are older than those of the Blue River and Detroit Dam districts.

#### Ages of Plutonism and Mineralization

A summary of potassium-argon age determinations for plutonic rocks, magmatic minerals, and associated products of hydrothermal alteration in the Cascade Range is presented in Table 2. The ages of

plutonic host rocks and associated hydrothermal mineral deposits from the Western Cascades of Oregon and southern Washington range from 7 to 22 m.y. and they are remarkably consistent with those ranging from 6 to 22 m.y. for similar rocks and deposits from the Cascades of central and northern Washington. Thus, the linear distribution and broad temporal concordance of plutons and mineral deposits throughout the Cascade Range collectively suggest a single, large, elongate magmatic-metallogenetic province. Although differing locally in geologic details, these plutons, mineral deposits, and related volcanic country rocks are characteristic of most of the entire circum-Pacific region.

The ages of plutons in the Washougal (20 m.y.), North Santiam (13 m.y.), Blue River (13 m.y.), and Bohemia (22 m.y.) districts, as recently reported by Power and others (1981) as part of this investigation, are consistent with the geology of these areas. Intrusions that comprise the Champion and Silver Star stocks of the Bohemia and Washougal districts, respectively, are the oldest in the Western Cascades, and they also intrude the oldest volcanic host rocks. The age of the Champion stock (22 m.y.) in the Bohemia district is concordant with that of the Cloudy Pass batholith (22 m.y.; Tabor and Crowder, 1969, and Field and others, 1974) and is slightly younger than early phases of the Tatoosh plutonic complex (24 to 26 m.y.) dated by Mattinson (1973) using the uranium-lead method. The Silver Star stock (20 m.y.) of the Washougal district is somewhat younger than these oldest plutons, and it is slightly older than the Snoqual-

Table 2.

Summary of K-Ar age determinations for Tertiary plutons and associated mineral deposits in the Cascade Range of Washington and Oregon (ages in millions of years and locations listed from north to south)

<u>Pluton-Deposit-Host</u>	<u>Age</u>	<u>Material Dated and Reference</u>
Cloudy Pass batholith	22	magmatic biotite (1)
Glacier Peak Porphyry	22	magmatic biotite (2)
	21	hydrothermal sericite (2)
Silver Creek Porphyry	17	rock; hyd. biotite-sericite (3)
Snoqualmie batholith	18	magmatic biotite (4)
North Fork Porphyry	10	rock; hyd. biotite (3)
Tatoosh pluton	15	magmatic biotite (5)
	13	magmatic biotite (5)
American River Porphyry	6	rock; hydrothermal sericite (3)
McCoy Creek Porphyry	24	rock; hydrothermal sericite (3)
Margaret Porphyry	16	rock; hyd. sericite-biotite (3)
Washougal District		
granodiorite	20	rock (11)
breccia pipe	19	rock; hydrothermal sericite (11)
Still Creek pluton	12	rock (6)
Laurel Hill pluton	8	magmatic hornblende (7)
North Santiam District		
granodiorite	13	magmatic hornblende (11)
breccia pipe	11	rock; hyd. biotite-sericite (8)
breccia pipe	10	hydrothermal sericite (9)
Detroit stock	7	rock (10)
Blue River District		
granodiorite	13	rock (11)
Nimrod stock	16	rock (10)
Bohemia District		
granodiorite	22	rock (11)

References:

- (1) Tabor and Crowder, 1969.
- (2) Field and others, 1974.
- (3) Armstrong and others, 1976.
- (4) Baadsgaard and others, 1961.
- (5) Fiske and others, 1963.
- (6) Wise, 1969.
- (7) Bikerman, 1970.
- (8) Richard L. Armstrong, 1981, personal communication.
- (9) James P. Matlock, 1981, personal communication.
- (10) Sutter, 1978.
- (11) Power and others, 1981; see Appendix 4 for locations and brief descriptions of these samples.

mie batholith (18 m.y.; Baadsgaard and others, 1961). Plutons of the Blue River and North Santiam districts (13 m.y., each) are similar in age to the youngest phases of the Tatoosh complex (13 to 15 m.y.; Fiske and others, 1963, and Mattinson, 1973) and to the Still Creek Pluton (12 m.y.; Wise, 1969) near Mt. Hood.

The almost invariable spatial coincidence of hydrothermal mineral deposits and plutons suggests a genetic association. This inferred relationship is additionally supported by a temporal association whereby the ages of hydrothermal minerals at Glacier Peak and the Washougal and North Santiam districts are similar to but a few million years younger than, those of nearby magmatic minerals. Thus, the crystallization of plutons and subsequent hydrothermal activity are intimately related both in space and time; as noted by previous investigators and elsewhere in the Pacific Northwest (Field and others, 1974).

Radiometric studies by McBirney and others (1974), Armstrong (1975), and Sutter (1978) have documented important episodes of volcanic activity during the intervals of 0-2, 3-6, 8-11, 14-18, and 19-40 m.y. in the central Oregon Cascades. The episodic history of Cascade magmatism was reinforced by ages obtained by Armstrong and others (1976) for plutons and related porphyry-type deposits in the Cascade Range of Washington and in Alaska. Most of the new dates reported by Power and others (1981) for the Western Cascades are concordant with these magmatic episodes. However, the 13 m.y. ages of plutons from the North Santiam and Blue River districts fall between

two episodes. Perhaps plutonism in the Western Cascades was either more continuous than the episodic volcanism, or the plutons solidified from magmas related to earlier episodes of volcanism because of slower rates of crystallization at depth.

## MINING DISTRICTS

This chapter contains a brief summary of the records of exploration and production and the salient features of the geology, mineral deposits, and effects of hydrothermal mineralization for each of the principal mining districts of the Western Cascades. This historical perspective draws heavily upon the prior efforts of Callaghan and Buddington (1938), Brooks and Ramp (1968), Mason and others (1977), and Moen (1977). The mineralized terrain of interest from north to south includes the Washougal and North Santiam districts, the Detroit Dam area, and the Quartzville, Blue River, Fall Creek, Bohemia, and South Umpqua districts. The isolated Al Sarena and Barron mines are probably a southerly continuation of the Western Cascades metallogenetic province.

According to the historical records summarized by Brooks and Ramp (1968), the earliest discovery of mineralization was in 1858 at the Bohemia district, and the last in 1910 at the South Umpqua district. Nearly all of the discoveries, as has been repeatedly the case throughout the cordillera of North and South America, were made on the recognition of placer gold found locally in stream gravels, and (or) of gold- and copper-bearing veins exposed nearby in bedrock. Subsequent exploration and mining endeavors have been largely directed toward the precious metals, particularly gold. Only recently have exploration programs given due consideration to the base metals, especially copper and potential by-product metals associated

with porphyry-type deposits. The emphasis given to gold and silver is documented by the production record for mining districts of the Western Cascades as summarized in Table 3 (after Brooks and Ramp, 1968; Mason and others, 1977; and Moen, 1977). Mining operations were most active during the period from 1892 to 1946. The total value of metals recovered during the years of production is about \$1,414,000, but it would probably exceed \$18,500,000 on the basis of current (1981) prices. However, early records are incomplete and metal production from the Blue River, Quartzville, and possibly other districts may be understated. The production data tabulated in Table 3 clearly underscore the importance of the precious metals, particularly gold, to the historical economies of the Western Cascade mining districts. For example, although the base metals (copper, lead, and zinc) accounted for 98.5 percent of the metal production by weight, they generated only 2.5 percent of the revenues. Gold amounted to only 0.9 percent by weight of all metals produced, yet it contributed 96 percent of the total revenues. Thus, the properties of this region were principally gold mines that incidentally recovered marketable but economically unimportant quantities of silver, copper, lead, and zinc.

The reference to these deposits as being gold mines necessitates some qualification. In addition to having produced insignificant quantities of gold, the mines of the Western Cascades also have received little scientific publicity in the geologic literature. Published records indicate that both districts and mines were small

Table 3. Summary of metal production and revenues for mining districts and some mines of the Western Cascades

<u>District/Mine</u>	<u>Copper</u>	<u>Zinc</u>	<u>Lead</u>	<u>Silver</u>	<u>Gold</u>	<u>Total</u>
Washougal	1,898 lb	- lb	- lb	120 oz	- oz	\$ 573
North Santiam	41,172	110,063	40,700	1,412	454	25,000
Detroit Dam		(no record of production)				
Quartzville	-	-	-	2,920	8,557	181,255 <sup>+</sup>
Blue River	257	-	-	17,162	7,728	174,000 <sup>+</sup>
Fall Creek		(no record of production)				
Bohemia	14,831	5,550	120,816	9,567	28,285	1,000,000
South Umpqua		(no record of production)				
Al Sarena	-	-	minor	minor	major	24,000
Barron	-	-	-	major	minor	9,000
<u>Total Revenues</u>						<u>\$1,413,828<sup>+</sup></u>
<u>Summary by</u>						
weight (lb)	58,168	115,613	161,516	2,138	3,087	340,522
percentage	17.1%	34.0%	47.4%	0.6%	0.9%	100%
value* (\$)	11,634	9,249	11,306	20,268	1,260,700	1,313,157 <sup>*</sup>
percentage	0.9%	0.7%	0.9%	1.5%	96.0%	100%

\* summary of metal values based on assumed prices of \$0.20/lb copper, \$0.08/lb zinc, \$0.07/lb lead, \$0.65/oz silver, and \$28.00/oz gold; uncertainties of true price and production precludes equality of total revenues and total value.

when active and that the production of ore was mostly infrequent. Although visible gold was observed as high-grade pockets in the weathered and limonite-stained outcrops of some veins, distributions beneath the surface were shallow and erratic. Commercial concentrations of gold in the veins rapidly vanished with increasing depth below the near-surface zones of oxidation, and in spite of downward continuity of vein structures and associated products of mineralization. Comparisons with respect to size and grade, geometrical configuration, host rocks, and associated metals and minerals suggest that the deposits of the Western Cascades have little in common with the better-known standards of the precious metals industry such as the gold-quartz veins of Precambrian and younger terrain, Carlin-type occurrences of finely disseminated gold, and the Bonanza-type epithermal gold-silver deposits of the Basin and Range. The erratic and near-surface distribution of the higher gold values in these veins is not generally compatible with that attributable to primary, or hypogene, processes of hydrothermal ore deposition. It is more consistent with secondary, or supergene, processes of ore deposition. This would include the surficial effects of residual concentration, and possibly that of secondary enrichment via solution-redeposition as recently discussed by Evans (1981), attendant with oxidation of the gold-bearing sulfide veins. Provided this interpretation is correct, the gold-bearing veins of the Western Cascades do not warrant a distinct classification on the basis of this metal. These veins are straightforward representations of cordilleran hydrothermal

mineralization that range nearly the full spectrum of the temperature-depth zone subclasses (hypothermal, mesothermal, and epithermal) as proposed by Lindgren (1933). The ores typically have high ratios of base to precious metals. Their location, distribution, and component metals are controlled by temperature and possibly by depth (pressure), which in turn vary systematically with respect to proximity to nearby plutons, structural channelways, and hydrothermally altered host rocks. The "ideal" hydrothermal system is characterized by vertical and lateral zonations of metals and minerals. Diagnostic metals of these zones include molybdenum and copper (sometimes tin, tungsten, and uranium) in the deeper and higher temperature ( $300^{\circ}$  to  $>500^{\circ}\text{C}$ ) hypothermal ores; copper, zinc, and lead in the intermediate ( $200^{\circ}$  to  $300^{\circ}\text{C}$ ) mesothermal ores; and lead and higher concentrations of silver and gold (sometimes mercury, arsenic, and antimony) in the shallower and lower temperature ( $<200^{\circ}\text{C}$ ) epithermal ores. Ideally, the porphyry-type deposits of copper and molybdenum consist of disseminated and veinlet-controlled minerals that occupy large volumes of rock in the deep central core of a hydrothermal system. The structurally-controlled vein deposits, or replacement deposits where carbonates serve as the host rock, extend several thousands of feet upward and outward from the deep submagmatic core. Ores of these vein and (or) replacement deposits are commonly polymetallic, and they may exhibit changing metal ratios that are dominated successively by copper, zinc, lead, and silver-gold with increasing distance from the deep central core.








The rationale for the zonal distribution of hydrothermal metals and minerals is derived largely from geologic observations. Although they have some qualitative application to mineral exploration programs, the zonations are normally transitional, not abrupt, and rarely are they fully developed in a single hydrothermal system, except possibly at Bingham, Butte, and a few other mining districts. Nonetheless, the production data for the Western Cascades (see Table 3) crudely express several imperfect regional trends. These include, from south to north, generally increasing ratios of (1)  $(\text{Cu} + \text{Zn} + \text{Pb})/(\text{Ag} + \text{Au})$ , (2)  $\text{Cu}/(\text{Ag} + \text{Au})$ , and (3)  $\text{Cu}/(\text{Pb} + \text{Zn})$  in ores recovered from the districts. Although metal ratios based on production data are unlikely to be representative of true values because of distortions imposed by economic and technological factors, the trends are believed to be generally valid and they clearly illustrate the importance of precious metals in the southernmost mines and districts versus base metals, especially copper, in the northernmost. Moreover, the metal ratios in combination with the principle of hydrothermal metal zonations collectively suggest the near-surface exposure of increasingly deeper and higher temperature mineralization from south to north along the Western Cascades. This inference is further substantiated by recent discoveries of porphyry-type deposits in the North Santiam and Washougal districts.

The remainder of this chapter is devoted to brief summaries of each of the mining districts and the southernmost isolated mines. Specific contributions of previous investigators, particularly the

thesis research efforts of my former colleagues, are cited wherever appropriate and the reader is referred to their maps and reports for additional detail and elaboration. Pairs of maps that synthesize the important features of the geology and mineralization are provided for most of the districts, and a standardized legend for these illustrations is given in Figure 16. The emphasis is directed to those characteristics that are diagnostic of and (or) are closely associated with porphyry-type mineralization. These would include the plutons, breccia pipes, zones of hydrothermal alteration, and metallic mineral assemblages, and their distributions and compositional-textural variations with respect to one another and to faults, shear zones, veins, and the mines and prospects.

Some clarification of terminology is warranted in reference to the physical occurrences of mineralization and to the types of hydrothermal alteration. Veins and veinlets represent open-space cavity fillings of ore and gangue minerals along structurally controlled and through-going faults, fractures, and shear zones. The boundaries of vein-type mineralization are normally well-defined as they are determined essentially by those (length, depth, and width) of the controlling structure. In contrast, disseminated mineralization is formed by the replacement of pre-existing minerals that serve as receptive hosts for the metallic and nonmetallic constituents of the hydrothermal fluids. Although the boundaries of disseminated-type mineralization are grossly controlled by structures, as these provide the channelways for the fluids, they are likely to be more diffuse

## GEOLOGIC MAPS

-  Tbx, hydrothermal breccia pipe.
-  Tgdp, granodiorite porphyry; Qgdp, quartz diorite porphyry.
-  Tg, granite; Tqm, quartz monzonite; Tgd, granodiorite.
-  Tqd, quartz diorite; Td, diorite; Ta, intrusive andesite;  
Tc, chilled border phase; Tmd, microdiorite;  
Tdi, undifferentiated dioritic intrusions.
-  Tv, undifferentiated volcanics.
-  Shear Zone
-  Fault

## ALTERATION/MINERALIZATION MAPS





- x Prospect or Mine
- / Vein                      Δ Breccia Pipe
-  Propylitic Alteration (District - Wide)
-  Argillic/Phyllic Alteration
-  Tourmaline-Quartz Alteration
-  Potassic Alteration

Figure 16. Standardized legend for geologic and alteration-mineralization maps of the Western Cascades.

and extensive than those of the controlling structures. The localization of copper- and molybdenum-bearing minerals in porphyry-type deposits typically involves both structural and replacement controls, but mineralization affects larger volumes and tonnages of rock and is in lower concentrations than mineralization in vein- or replacement-types of deposits. The ore minerals are present both as veinlets occupying thin, closely-spaced, and intersecting fractures and as discrete disseminated replacements in the host rocks between these fractures.

The terminology with respect to hydrothermal alteration generally follows the conventions of Creasey (1966), Meyer and Hemley (1967), Rose (1970), Lowell and Guilbert (1970), Field and others (1975), and Rose and Burt (1979). The alteration minerals occur as secondary replacements of the primary rock-forming minerals as a consequence of reactions between host rocks and the hydrothermal fluids. Common and widespread are associations or groups of two or more alteration minerals. Provided such minerals are paragenetically equivalent and represent compatible assemblages in terms of phase equilibria, the associations suggest at least partial equilibrium of rock-fluid reactions during the hydrothermal event. The type or kind of alteration is specified by the presence of one or more critical or diagnostic minerals. Accordingly, potassic alteration is defined by the presence of hydrothermal biotite and (or) potassium feldspar; phyllic alteration by sericite; argillic alteration by minerals of the kaolinite and montmorillonite groups; and propylitic alteration

by one or more minerals such as albite, calcite, chlorite, epidote, zeolite, and probably others. Quartz is not diagnostic as it is compatible with all four alteration types. Other "diagnostic" minerals such as albite, calcite, chlorite, clays, and sericite may be found in several alteration types for reasons of compatibility, disequilibrium, metastability, and (or) paragenesis. Abundances of these minerals normally vary with the intensity of alteration and may range from small (1 percent) to large (50 percent). Many of these minerals may also occupy veinlets as open-space fillings where the alteration is pervasively intense. The effects of phyllic and argillic types of alteration are usually readily evident as the host rocks are conspicuously bleached. However, in this thesis, the two types are combined as a single argillic-phyllic assemblage because the mineral components are typically finely crystalline, intermixed, and difficult to identify except by X-ray methods of analysis. Although the tourmaline-quartz assemblage is not a formal alteration type, it is easily recognized in the field. However, except in parts of the Washougal District, this assemblage is not sufficiently extensive to constitute a distinct mappable unit. Occurrences of tourmaline in the Western Cascades and elsewhere are most commonly associated with breccia pipes, potassic and phyllic types of alteration, and copper mineralization. Detailed studies of some well-known mining districts (see Rose, 1970; Lowell and Guilbert, 1970; Gustafson and Hunt, 1975; and references cited therein) have demonstrated that the major alteration types generally exhibit a three-dimensional zonation.

This zonation is crudely analogous to that of the cogenetic metals and ore-bearing minerals previously described. Potassic alteration defines the deep innermost core of the hydrothermal system, whereas propylitic alteration marks the higher, outermost, and a most extensive peripheral fringe. Irregular zones of phyllic and argillic alteration, which may be controlled by structure and accompanied by abundant pyrite, occupy intermediate positions between the potassic core and propylitic fringe. Most importantly, the large, low-grade porphyry-type deposits of copper and molybdenum are uniquely coincident with the zone of potassic alteration, and sometimes in association with the tourmaline-quartz assemblage and phyllic alteration as well. The structurally controlled vein-type deposits of base and precious metals extend outward and upward through the fringing zone of propylitic alteration, but locally may be contained within smaller tabular zones of phyllic and argillic alteration.

#### Washougal District

The Washougal mining district is located in Skamania County, Washington, approximately 30 miles northeast of Portland, Oregon. It represents the southernmost district of the Washington Cascades and was established during the latter part of the 1890's following the discovery of gold and copper along drainages near the headwaters of the Washougal River and the East Fork of the Lewis River (Moen, +1977). Thereafter, several hundred claims were staked, a few prospects underwent extensive subsurface development, and a number of

mills were constructed. In spite of this activity, the total recorded production to date has been negligible because of an apparent limited quantity of ore and (or) ruinous forest fires. It consists of copper and silver valued at only \$573 that was derived from the Last Chance, Miner's Queen, and Skamania mines (Patty, 1921; Moen, 1977). An extensive exploration program that was initiated by Amoco Minerals Company in 1974, following prior investigations by several companies and the U.S. Bureau of Mines, has since identified porphyry-type mineralization in association with breccias at and near the Miner's Queen property (Moen, 1977). Other participating companies are now undertaking more detailed exploration and evaluation of this significant discovery.

Various aspects of the geology and mineralization of the Washougal district have been described by Heath (1966), Grant (1969), Moen (1977), Schriener (1978), Shepard (1979), Birk (1980), and Schriener and Shepard (1981). The general geologic relationships of this district are illustrated in Figure 17. Country rocks consist of volcanoclastics and flows of basalt and andesite, which are possible equivalents of the Ohanapecosh Formation of Eocene to Oligocene age according to Schriener (1978). These volcanic rocks are intruded by a number of plugs and a large composite stock designated the Silver Star plutonic complex. Individual phases of the complex range from diorite to granite aplite in composition, but the bulk of the intrusion consists largely of granodiorite and quartz diorite. At least



30 tourmaline-bearing breccia pipes have been mapped throughout the district (Schriener and Shepard, 1981). Although the pipes intrude both plutonic and volcanic rock units, most are associated with the granodiorite phase of the complex. Bedrock of the Washougal district has been gently deformed by a series of northwest-trending folds and faults (Hammond and others, 1977). Schriener and Shepard (1981) have noted a strong correlation between the orientations of faults, joints, and elongate protrusions of the Silver Star stock and the trends of lineaments observed from aerial photographs. These suggest that pre-existing regional structures with northwest and north-northeast trends controlled both the emplacement of the plutonic complex and the location of subsequent hydrothermal mineralization. Important features relating to hydrothermal mineralization in the Washougal District are summarized in Figure 18. The ore and gangue minerals occur as open-space fillings that occupy veins, veinlets, and cavities in the breccias, and as finely to coarsely crystalline replacements disseminated in the host rocks and breccias. The principal sulfide minerals include pyrite, chalcopyrite, bornite, pyrrhotite, galena, sphalerite, and molybdenite with which trace amounts of gold and silver are associated. Minerals formed by oxidation and secondary enrichment are limonite, malachite, chrysocolla, azurite, brochantite, descloizite, chalcocite, and covellite according to Schriener (1978), Shepard (1979), and references cited therein. The dominant gangue mineral of veins is quartz, whereas alteration minerals replacing the host rocks are numerous and include variable

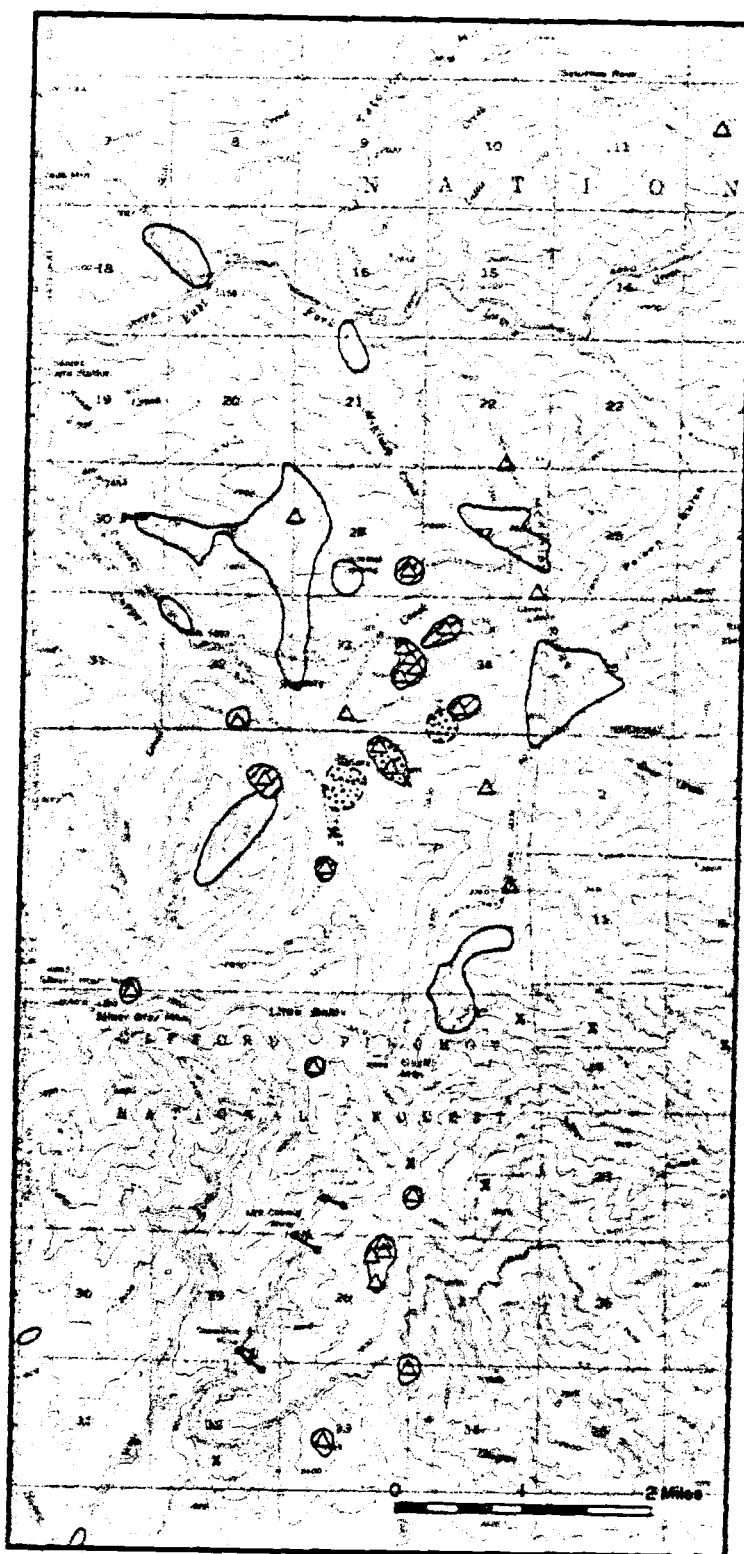


Figure 18. Mineralization summary of the Washougal District.

amounts of actinolite, albite, biotite, carbonate, chlorite, clays, epidote, magnetite, potassium feldspar, quartz, sericite, specular hematite, tourmaline, urallite, and zeolites. Vein-type mineralization is most extensively developed in the southern and eastern parts of the district. Veins trend predominantly northwest and are steeply dipping.

The Washougal District exhibits a poorly developed district-wide zonation of metals and minerals. According to Moen (1977) and other investigators, veins localized within and near the contacts of the Silver Star plutonic complex are characterized by relatively higher  $\text{Cu}/(\text{Pb} + \text{Zn})$  ratios than are those in volcanic country rocks beyond the margins of the intrusion.

Porphyry-type mineralization crops out along Copper and Miners Creeks (unsurveyed area immediately south of sec. 33, T. 4 N., R. 5 E.) at the Black Jack and Miner's Queen prospects in the northern part of the district. It is intimately associated with tourmaline-bearing breccia pipes and zones of potassic alteration (see Fig. 18). This type of copper-molybdenum metallization formed at higher temperatures than that of the lead-zinc-copper vein deposits as is indicated by associated mineral assemblages containing chalcopyrite, bornite, magnetite, pyrrhotite, molybdenite, tourmaline, biotite, actinolite, potassium feldspar, sericite, and quartz.

Most rocks of the Washougal District have been propylitized to assemblages that may include chlorite, sericite, epidote, quartz, calcite, magnetite, albite, and zeolites. Areas of phyllic and

argillic alteration are restricted to hydrothermal breccias, shear zones, and the hornfels associated with the emplacement of the stock. Quartz, sericite, tourmaline, clay, and pyrite are common products of this type of alteration. Potassic alteration to an assemblage that includes potassium feldspar and biotite is found only in a restricted area at the Miner's Queen and Black Jack prospects, the sites of porphyry-type copper mineralization.

#### North Santiam District

The North Santiam mining district is located in eastern Marion County approximately 38 miles east of Salem, Oregon. It represents the northernmost of the principal districts that comprise the Western Cascades subprovince of Oregon. Most of the early history of this district has been lost. According to Callaghan and Buddington (1938), claims were initially staked in the 1860's, but development apparently did not begin until the late 1890's. Total recorded production from veins of the district is valued at \$25,000 for zinc, copper, lead, silver, and gold. However, this value is probably low because the output of many properties was never reported. The most productive mines have been the Ogle Mountain (gold), the Santiam Copper (copper, gold, and silver), and the Ruth (formerly the Amalgamated; zinc, gold, silver, and lead). As of 1978, a redevelopment program was being conducted at the Ruth Mine by the Shiny Rock Mining Company. During the past five years, both the Freeport Exploration Company and Amoco Minerals Company have successfully

encountered porphyry-type mineralization as a consequence of detailed exploration and diamond drilling programs. Information concerning the mines and prospects of the district can be found in reports by Callaghan and Buddington (1938) and Brooks and Ramp (1968). In addition, Leever (1941) has described some of the mines and provided a petrologic study of their ores. Most recently, Olson (1978) has mapped a large part of the district and has included a discussion of the general characteristics of hydrothermal mineralization.

The principal geologic features of the North Santiam district are illustrated in Figure 19. Country rocks are largely tuffs, polymictic breccias, and flows of andesite and basalt which belong to the Sardine Formation of middle Miocene age. They have been intruded by a plutonic complex having three distinct phases that consist of microdiorite, diorite, and porphyritic granodiorite. The emplacement of plutonic magma arched the country rocks vertically upward to form a poorly-developed dome. Other structural elements of the district include faults, fractures, and shear zones that are steeply dipping and trend both to the northwest and northeast. However, the northwest trend is most pronounced according to Olson (1978). It consists of two possibly conjugate sets, striking N. 20° W. and N. 60° W., that have exerted a dominant control on the emplacement of early andesite dikes and the localization of later mineralized veins, shear zones, and breccia pipes.

The distributions of veins, prospects, and areas of intense hydrothermal alteration are depicted in Figure 20. Hydrothermal

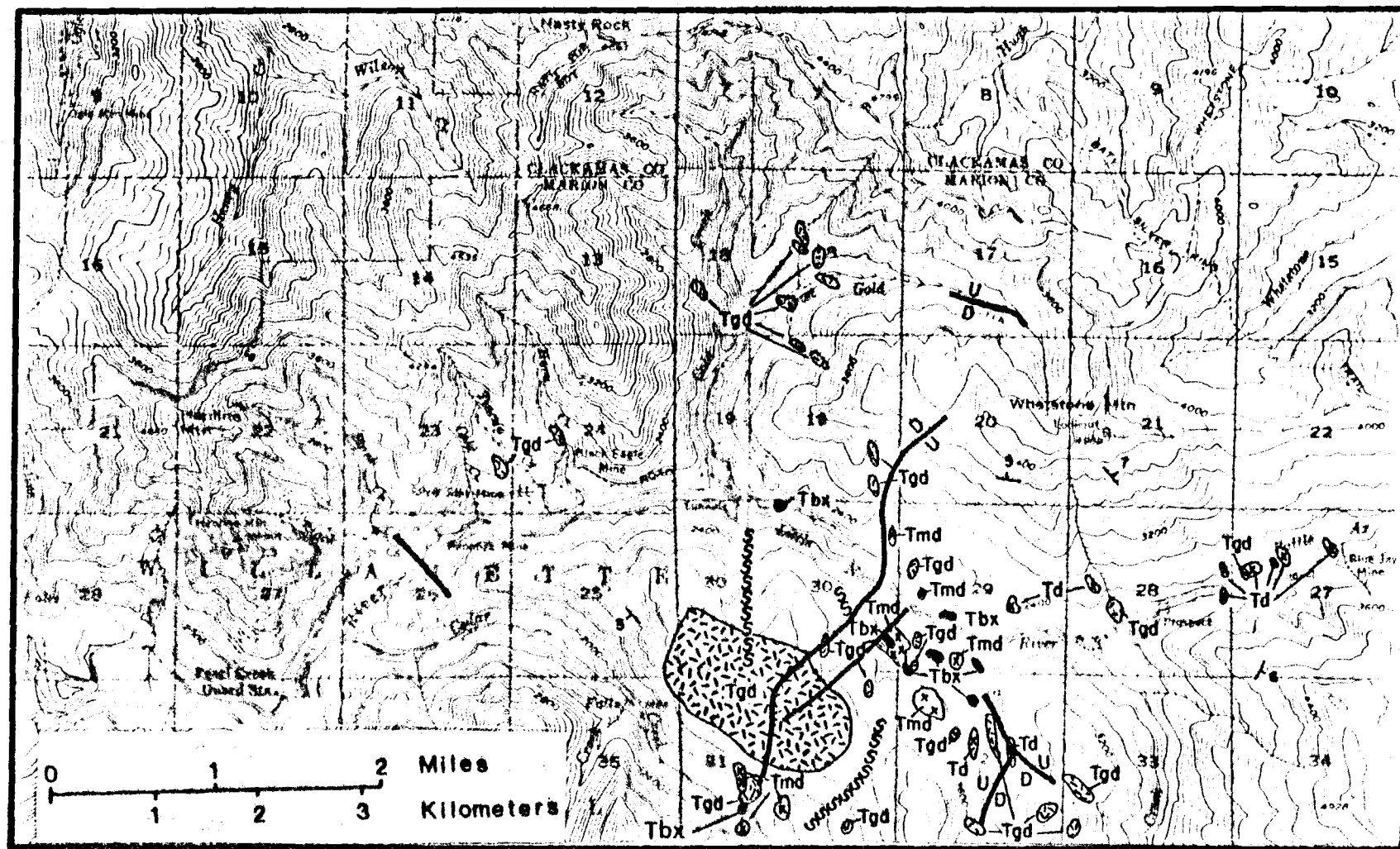


Figure 19. Geologic summary of the North Santiam District

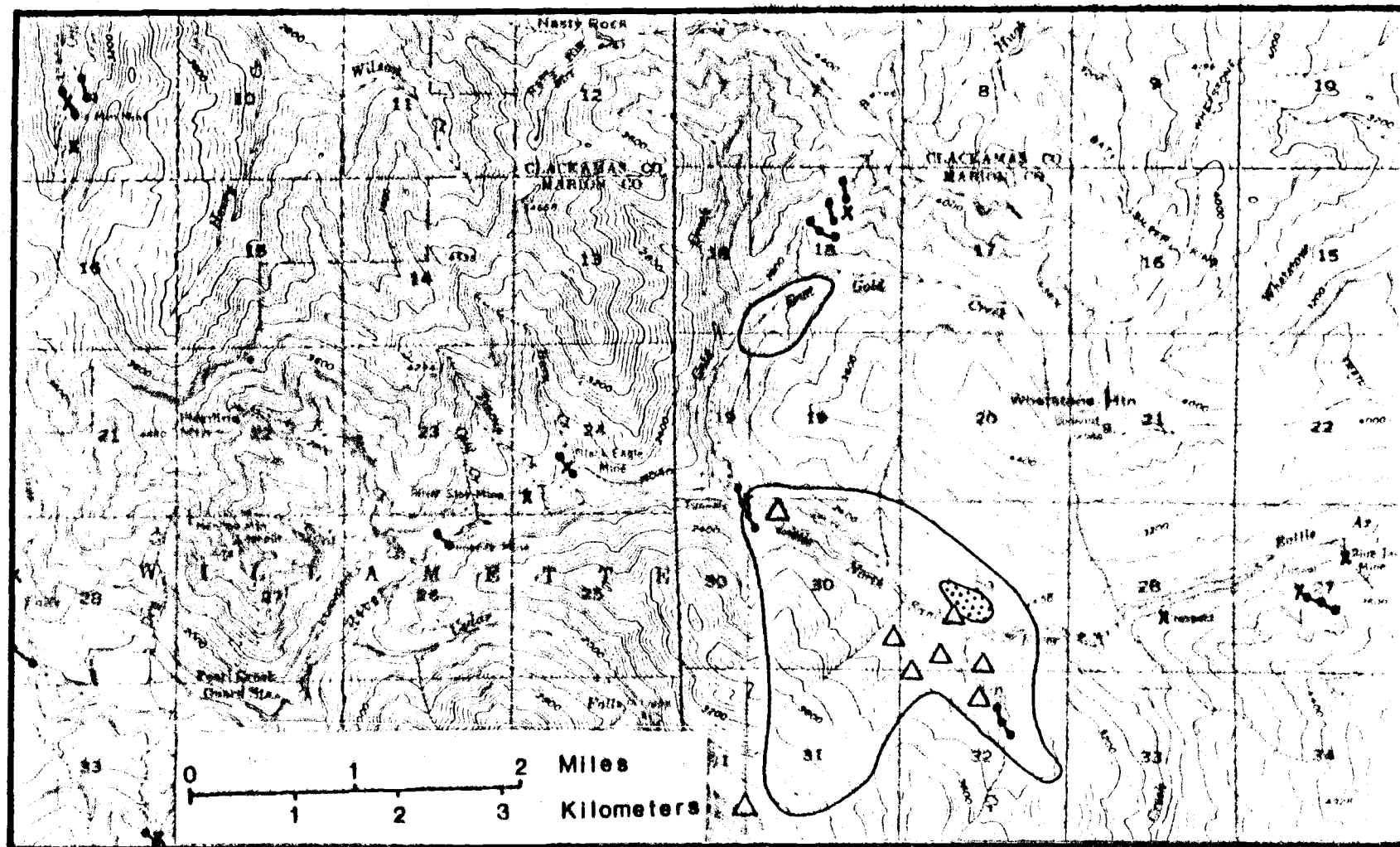


Figure 20. Mineralization summary of the North Santiam District.

deposition of sulfides exhibits two principal modes of occurrence in the North Santiam district. One consists of cavity fillings in structurally controlled veins, veinlets, and shear zones, which is historically most important, and the other of disseminated replacements in host rocks and breccias that occupy larger areas and is representative of porphyry-type mineralization. The veins trend northwest and are steeply dipping. They contain pyrite, chalcopyrite, sphalerite, and galena as the dominant sulfides. The common gangue minerals are quartz, barite, specular hematite, carbonates, chlorite, sericite, epidote, magnetite, tourmaline, and clays. Although the veins are most abundant in the andesitic flows, the intrusions may also serve as host to this type of mineralization. Many of the individual veins are symmetrically zoned. More importantly, the mineral components of these veins are zoned on a district-wide scale. Minerals such as chalcopyrite, magnetite, specular hematite, and small quantities of bornite and molybdenite are common to the central part of the district, and they are intimately associated with the tourmaline-bearing breccia pipes. Pyrite, coexisting with chalcopyrite, replaces specular hematite to form an intermediate zone around this central core. In the peripheral parts of the district, pyrite accompanied by sphalerite and galena predominate over all other sulfides. These mineralogical zonations, as previously noted, are common to other well-known hydrothermal districts. They indicate decreasing temperatures of mineral deposition outward from the central zone, which is inherent to the "ideal" hydrothermal system and characteristic of

mineral assemblages in veins associated with porphyry copper deposits. In fact, recent exploration has encountered porphyry-type mineralization at depth in diamond drill core. It is closely associated with the tourmaline-bearing breccia pipes and consists of pyrite, chalcopyrite, and minor bornite and molybdenite which may cover an area approximating one square mile on and near the common boundaries of sections 29, 30, 31, and 32 of T. 8 S., R. 5 E. The pipes (see Figure 20) are located at lower elevations in the central part of the district and are similar to those in the northern part of the Washougal district. They are composed of fractured and (or) displaced and rotated fragments of plutonic and volcanic country rock, exhibit northwesterly trends individually and collectively, and have been altered to assemblages of quartz, tourmaline, sericite, potassium feldspar, chlorite, and clay minerals. Sulfides may be accompanied by magnetite and (or) specular hematite as disseminations, veinlets, and cavity fillings of the breccia matrix. Gangue minerals associated with the metallic oxides and sulfides in micro-veinlets of the central zone are chiefly quartz, minor calcite, and traces of anhydrite, barite, and fluorite.

Hydrothermal alteration in the district includes the propylitic, phyllic, and potassic types. Propylitic alteration is widespread and typically includes minerals such as chlorite, epidote, calcite, quartz, albite, sericite, kaolinite, magnetite, and pyrite. Phyllic alteration is structurally controlled as inferred by its distribution and association with veins and breccia pipes. Common minerals of

this assemblage are quartz, sericite, kaolinite, and usually tourmaline. Potassic alteration is of small areal extent at the surface, but becomes more widespread at depth. Minerals associated with this type of alteration are biotite, quartz, sericite, chlorite, kaolinite, and occasionally potassium feldspar. The coincidence of potassic and phyllic types of alteration with plutons, breccia pipes, and disseminated-veinlet forms of porphyry-type mineralization, and at the deepest levels of exposure in the central part of this district, is not fortuitous in terms of modern metallogenetic theory.

#### Detroit Dam Area

Although lacking any historical records of past mining activity the Detroit Dam area is of interest because some features of its geology and mineralization are shared with other districts of the Western Cascades. It is situated along the boundary of Linn and Marion Counties, approximately 40 miles east-southeast of Salem, Oregon. The principal source of geologic information for this area is provided by Pungrassami (1970), and this has been complemented by more recent work by D. A. McLean (1980, personal communications). General geologic relations are summarized in Figure 21. The focal point of this area is the Detroit stock, the largest pluton in the Western Cascades of Oregon. It is essentially of uniform granodiorite composition, and it intrudes bedded tuffs, andesitic flows, and volcaniclastic sedimentary rocks of the Sardine Formation. Minor intrusive phases include dikes and sills of andesite in the volcanic

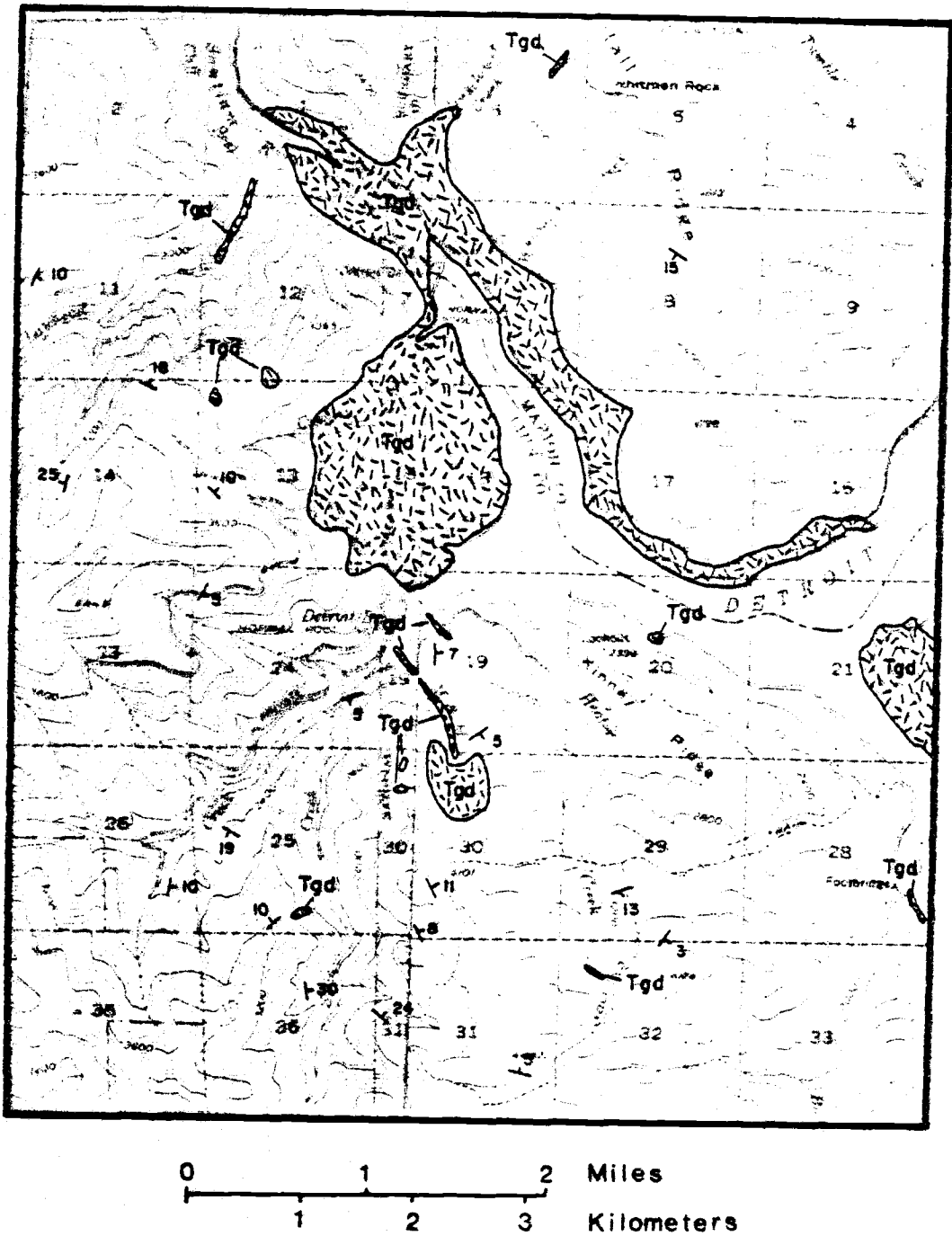


Figure 21. Geologic summary of the Detroit Dam Area.

country rocks, and mafic dikes within the granodiorite stock. Propylitic alteration is widespread throughout the area, as is typical of all other districts in the Western Cascades. The altered rocks commonly have chlorite, epidote, clay minerals, calcite, sericite, magnetite, and quartz as replacements of the primary mineral constituents. Amygdules of the volcanic flows are filled with chlorite, epidote, quartz, and pyrite. Thin selvages of argillic-phyllic alteration may be present along the margins of some mineralized structures. Although metallization is generally weak, pyrite is locally moderately abundant as open-space fillings of fractures and shear zones and as disseminations in the granodiorite and volcanic country rocks, particularly in sections 18 and 19 along the southwest arm of the Detroit Reservoir. These mineralized zones also contain trace amounts of chalcopyrite, galena, and sphalerite at a few localities. Samples of hydrothermally altered granodiorite commonly have anomalously high concentrations of copper as compared to their unaltered counterparts ( $>100$  ppm versus about 30 ppm). The orientations of granodiorite dikes, minor faults, and mineralized zones of shearing and closely spaced fractures collectively exhibit a pronounced northwest trend.

#### Quartzville District

This district is located in Linn County, about 45 miles southeast of Salem, Oregon. According to Callaghan and Buddington (1938), gold was first discovered in the Quartzville area in 1863. By 1871,

most of the mines had been abandoned, but many of these properties were relocated during the 1880's. There is considerable uncertainty with respect to the production records for this district. According to the Oregon Department of Geology and Mineral Industries (1951), production is 8557 oz gold and 2920 oz silver valued at \$181,255. As these figures are consistent with other published records, they are incorporated in Table 3. However, on the basis of these and other documents, Munts (1978) has obtained a substantially larger value (between \$365,000 and \$850,000) for total production in the district, including as much as \$500,000 that was not reported for the Lawler mine. Regardless of historical oversights, revenues were derived exclusively from the precious metals and in spite of the widespread occurrence of sulfides containing the base metals. The Lawler and Albany mines have been the main producers of the district. Although sporadic prospecting has continued to the present, most mining operations had ceased by 1900. Detailed information about the mines and prospects of this district is contained in reports by Callaghan and Buddington (1938), Brooks and Ramp (1968), and Stowell (1921). More recently, Gray (1977) has published a field trip guide to the area, and Munts (1978) has completed a detailed geologic map and up-to-date descriptions of the geology and mineralization, the principal conclusions of which have been briefly summarized by Munts (1981).

General geologic relationships of the Quartzville district are summarized in Figure 22. Most of the terrain consists of pyroclastic rocks and flows of basalt and andesite that have been correlated with



the Sardine Formation of middle Miocene age. However, the sequence also contains interbedded units of dacite and rhyodacite that are somewhat unusual for this formation. These volcanic country rocks have been intruded by a number of small plutons that range from diorite to quartz monzonite in composition. They include some of the most silicic (up to 78.0%  $\text{SiO}_2$ ) and potassic (up to 7.0%  $\text{K}_2\text{O}$ ) intrusions of the Western Cascades. Country rocks in the western part of the district have been gently deformed by the northeast-trending Sardine syncline. Numerous small faults and shear zones offset the strata. The dominant structural trend is to the northwest, as is indicated by the preferred orientations of the faults, dikes, and mineralized shear zones, veins, and fractures. On the basis of structure and the distributions of volcanic and plutonic rock types, Munts (1978) has concluded that the district occupies the eastern edge of a caldera complex.

Features pertinent to hydrothermal mineralization are portrayed in Figure 23. The ore and gangue minerals have two principal modes of occurrence. They are present as cavity fillings in structurally controlled fractures, veins, and shear zones, and as disseminated replacements in the host rocks. Veins in the Quartzville district trend predominantly northwest (see Fig. 23) and are steeply dipping. Although production data show that only gold and silver were extracted from the ores, metallic minerals contained in the veins include pyrite, sphalerite, and minor amounts of chalcopyrite, galena, tetrahedrite, bournonite, and stibnite, in addition to native

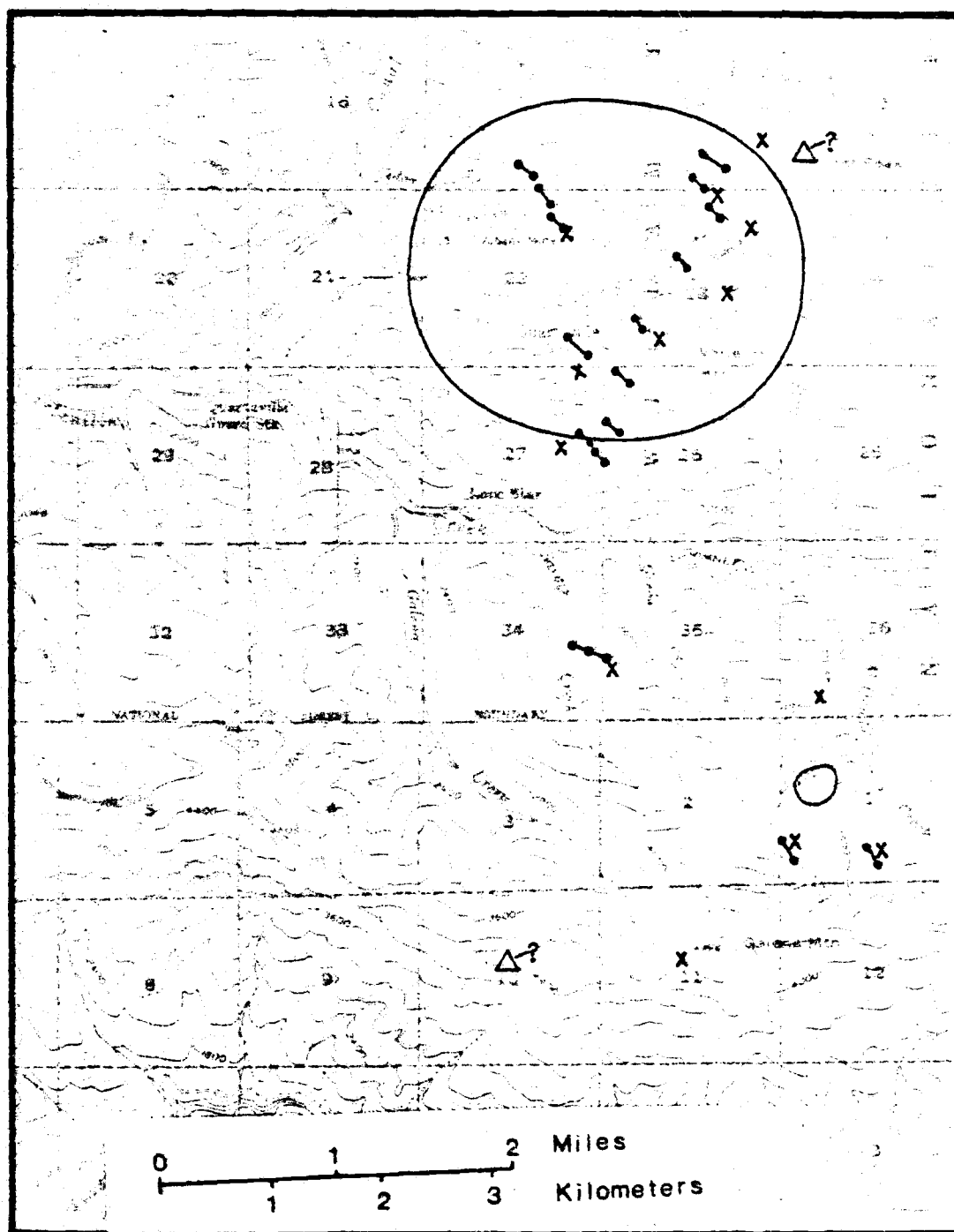


Figure 23. Mineralization summary of the Quartzville District.

gold. The most abundant gangue mineral is quartz, but carbonates, clays, and barite are also common. Munts (1978) has suggested there may be a district-wide zonation of metals and minerals. The central part apparently is characterized by gold, silver, and the sulfides of copper, lead, and zinc, whereas peripheral areas contain more abundant pyrite, stibnite, quartz, and calcite (possibly galena and tetrahedrite). These zonations are poorly established, at best. According to Munts (1978), larger areas of disseminated pyrite are particularly common to the rhyodacite unit along the northern side of Dry Gulch (secs. 22 and 23). Small amounts of chalcopyrite and bornite locally accompany the pyrite, and this zone of disseminated sulfides is coincident with minor occurrences of tourmaline and the large area of argillic-phyllic alteration depicted in Figure 23. Elsewhere, disseminated blebs and fracture-controlled stringers of pyrite, sphalerite, chalcopyrite, quartz, and calcite are present in pyroclastic host rocks at Sulphide Bridge (SW cor. sec. 25).

As in other districts of the Western Cascades, propylitic alteration is widespread in host rocks of the Quartzville area. Assemblages of this type contain one or more of minerals such as epidote, chlorite, calcite, quartz, zeolites, and pyrite. In the Dry Gulch area, as previously noted, a central core of siliceous phyllic alteration that is associated with disseminated sulfide mineralization grades outward transitionally into successive zones of argillic and less intense propylitic alteration (Munts, 1978). The phyllic assemblage consists of sericite, quartz, pyrite, and minor clay, and the

argillic assemblage of clays, quartz, pyrite, chlorite, sericite, and alunite (?). Outcrops of tourmaline-bearing breccia pipes have not been identified in this district. However, fragments of pipe-like breccia with tourmaline forming a matrix to volcanic clasts are present as float on the northwest side of Galena Mountain (sec. 11) and as boulders in nearby Galena Creek (Munts, 1978). Tourmaline is found in outcrops at several other localities in the northern part of the district (secs. 21, 22, and 14) as cavity fillings of veinlets, fractures, and tectonic breccias and as replacement "sunbursts" in the host rocks. In all occurrences the tourmaline is paragenetically associated with quartz and in close proximity to the cupolas of small intrusions.

### Blue River District

The Blue River district is in Linn and Lane Counties, approximately 40 miles east-northeast of Eugene, Oregon. It was established in 1887 following the discovery of the Lucky Boy deposit, which subsequently became the most important mine of the district. However, the free-milling gold at this property was rapidly exhausted and the closing of this mine in 1913 signalled an end to most activity in the area. Again, the production records for this district are uncertain. Figures listed in Table 3 for the recovery of silver, gold, and minor copper are those cited by Callaghan and Buddington (1938) for all ores mined from the district. However, the total value of this production (\$174,000) is that reported by the Oregon

Department of Geology and Mineral Industries (1951) and Brooks and Ramp (1968) for ores of the Lucky Boy mine. It includes some discrepancies in the metals produced (less silver, more copper and gold, and 1,051 lb. lead), but these differences would merely decrease the total by a few thousand dollars. More significant is the probability of \$50,000 to \$100,000 of unrecorded production. Descriptions of mines and prospects are given in reports by Callaghan and Buddington (1938) and Brooks and Ramp (1968). Much of the district has recently been mapped by Storch (1978) who has described the geology and general characteristics of the mineralization.

The dominant geologic features of the district are illustrated in Figure 24. Bedrock consists primarily of tuffs, tuff breccias, and flows of basaltic andesite and dacite of the Sardine Formation of middle Miocene age. These volcanic rocks have been intruded by several small plutons of granodiorite and quartz diorite. Volcanic country rocks have been gently deformed by a northeast-trending anticline in the western half of the district. Several northwest-trending shear zones have served to localize hydrothermal alteration and metallization.

The distribution of prospects, veins, and areas of intense alteration are shown on Figure 25. Sulfide minerals are present as cavity fillings of veins and coatings along fractures, and as disseminations impregnating nearby altered host rocks. Although both plutonic and volcanic rock units have been mineralized, the associated alteration is usually more widespread in the more porous volcaniclas-

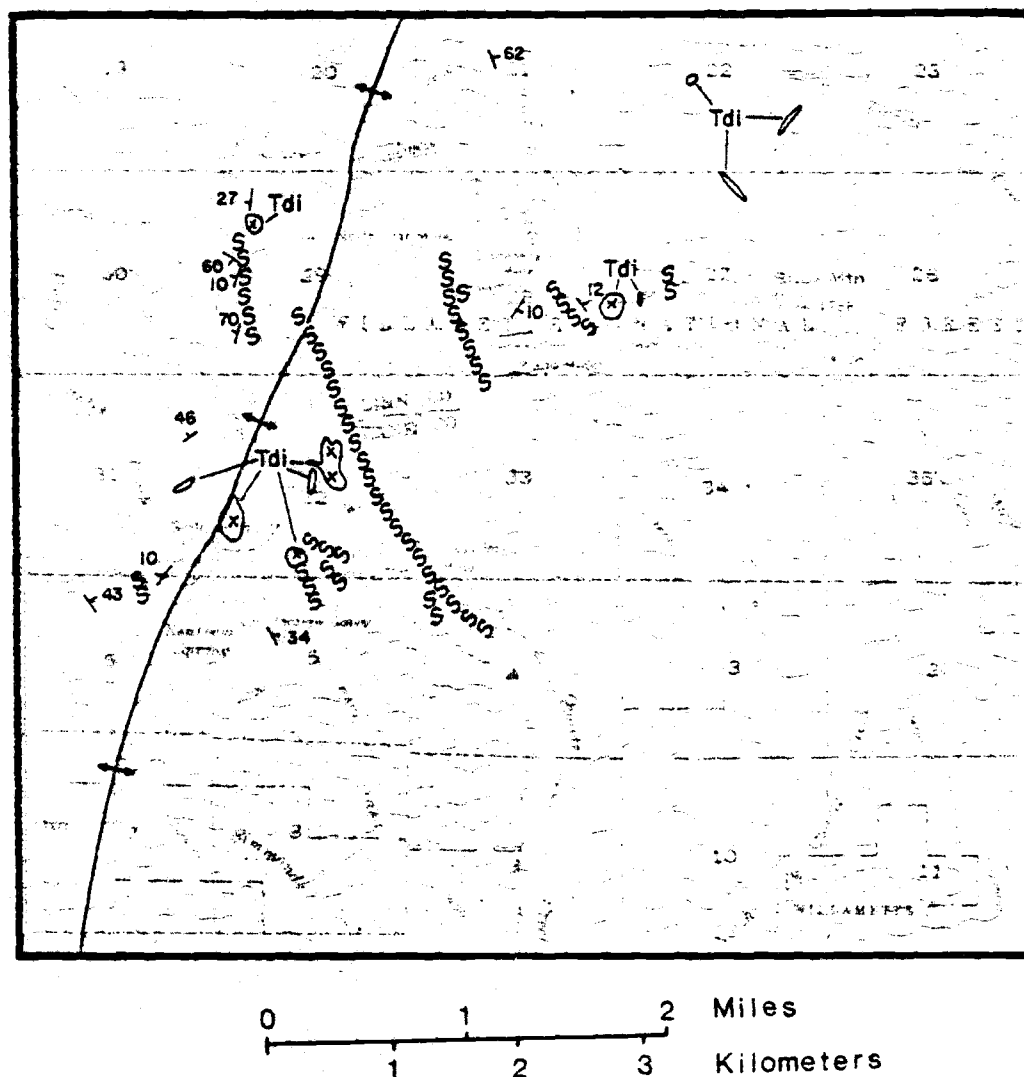


Figure 24. Geologic summary of the Blue River District.

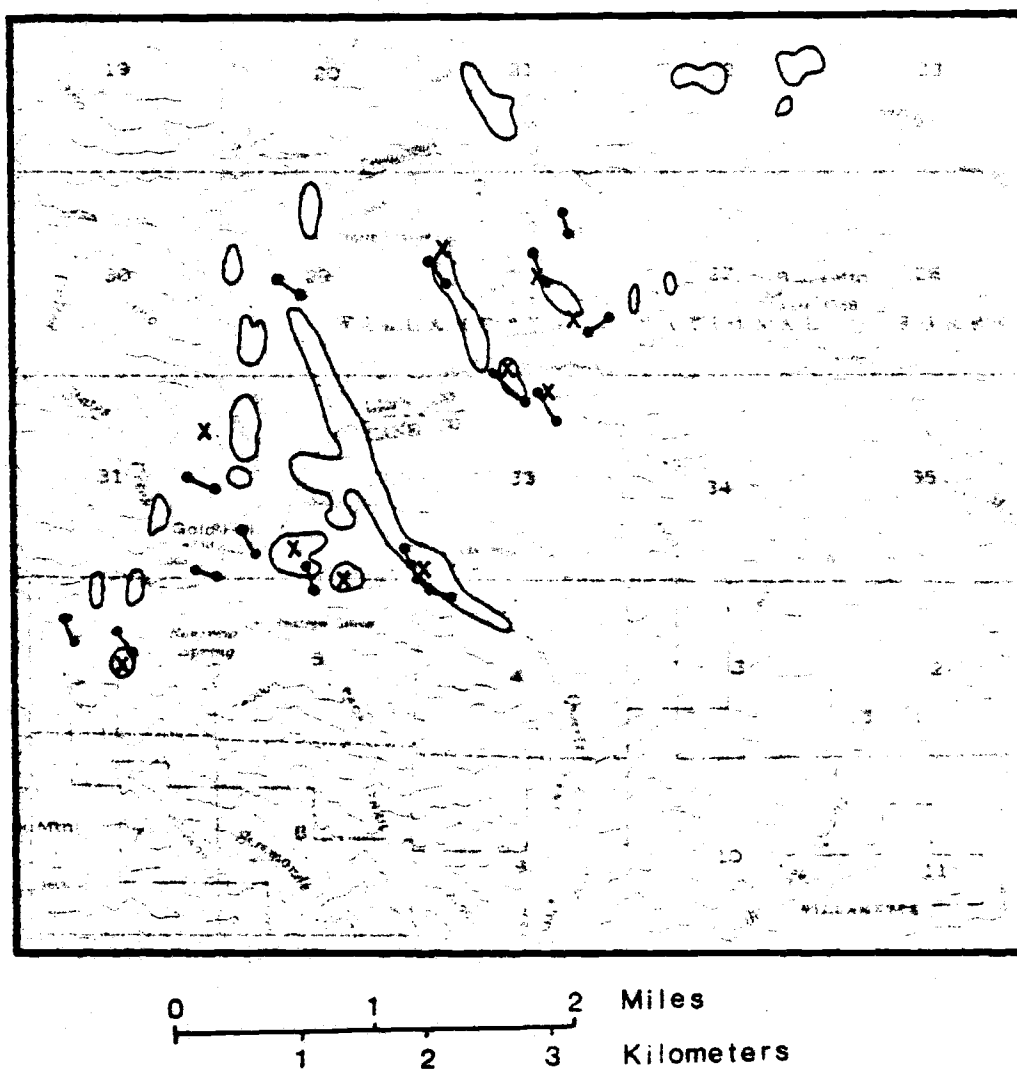


Figure 25. Mineralization summary of the Blue River District.

tic strata. The sulfide minerals are pyrite, sphalerite, galena, chalcopryite, and tetrahedrite. Common gangue minerals are quartz, calcite, and clays. Callaghan and Buddington (1938) have reported district-wide zonations of some vein minerals. Calcite is most abundant in veins from the northern part of the district, and chalcopryite is most common in the central part.

Propylitic alteration is ubiquitous with the host rocks having been replaced by mineral assemblages consisting of chlorite, epidote, calcite, albite, quartz, magnetite, pyrite, sericite, and zeolites. More intense types of argillic-phyllic alteration are locally common adjacent to the veins and shear zones. These mineral assemblages may include sericite, quartz, kaolinite, and disseminated pyrite which may completely replace the host. The preferred northwest orientation of veins, shear zones, and elongate patches of alteration is conspicuous, as is the case for districts previously described. However, the absence of larger size and composite plutons, breccia pipes, tourmaline, and zones of potassic alteration suggests that the Blue River district represents the upper parts of a hydrothermal system.

#### Fall Creek District

The Fall Creek district is in eastern Lane County, approximately 36 miles east-southeast of Eugene, Oregon. According to Stafford (1904), it was established in 1901 following the discovery of gold. Although there are no records of production, the district was actively prospected in 1903 and again in 1931, and the Ironsides mine was

operated on a small scale for a few years. Descriptions of the geology and prospects in the area are contained in reports by Callaghan and Buddington (1938) and Brooks and Ramp (1968).

Volcanic rocks of the district consist predominantly of pyroclastics that are intercalated with several flows of basalt and andesite. Peck and others (1964) have correlated these rocks with those of the Little Butte Volcanic Series of late Oligocene to early Miocene age. In addition to numerous dikes of basalt and andesite, Callaghan and Buddington (1938) noted a plug of dacite porphyry in the northwest part of the district, and found samples of augite diorite on the waste dump at the Jumbo prospect. The augite diorite is now exposed in a road-cut near this prospect, and it is similar in appearance to small dikes of diorite in the Blue River district. Flows of Quaternary basalt cap some ridges in the area. Bedrock of the district has been neither tilted nor deformed according to Callaghan and Buddington (1938). However, some of the mineralization is localized in poorly defined shear zones.

Because detailed studies have not been undertaken in this district recently, knowledge of the geology and mineralization is derived largely from that of Callaghan and Buddington (1938). They have mapped two large areas of alteration, and all prospects are confined to the one northwest of Christy Creek. Alteration of bedrock is principally to minerals of the propylitic assemblage, but zones of bleached and iron-stained outcrops are locally present. The latter are found in close proximity to a few poorly developed veins

and shear zones, and they are probably representative of argillic-phyllic alteration and the oxidation of disseminated sulfides in host rocks adjacent to these structures. Although most of these mineralized structures are diffuse and poorly defined, the majority of orientations that are discernible trend to the northwest. Pyrite is the only sulfide to have been identified from this district. The pyrite, or the limonitic product of its oxidation, is present both as vein fillings and as disseminations. Small amounts of gold are irregularly distributed in the oxidized veins and nearby altered host rocks. It is commonly associated with stringers of comb quartz in the veins, but not in rock or vein material that has been intensively silicified.

#### Bohemia District

The largest and most productive mining camp of the Western Cascades is the Bohemia district. It is in Lane County, about 42 miles southeast of Eugene, Oregon, and mines and prospects of the district cover more than 20 square miles. According to Callaghan and Buddington (1938), Brooks and Ramp (1968), and references cited therein, mineralization was first noted in 1858, but the district was not formally established until 1863 with the discovery of gold by James "Bohemia" Johnson and George Ramsey. Since that time, more than 2000 mining claims have been filed in the district and the value of metals recovered from the ores probably exceeds \$1,000,000. Although gold was clearly the most important contributor to the metal

revenues, the ores also yielded substantial amounts of lead, silver, copper, and zinc (Mason and others, 1977; see also Table 3). Because sphalerite and galena are of essentially subequal abundance in the ores, the small quantity of zinc relative to lead in the historical production records is likely an artifact of technology (recovery) and economics (smelter penalties). The district was active chiefly during the interval between 1890 and 1950, and the most important properties were the Champion, Helena, and Musick mines. For the past decade there has been a renewed interest in the Bohemia area. Several of the former mines have undergone redevelopment, and surface and subsurface exploration programs have been conducted for vein deposits of base and precious metals and for larger, low grade deposits of porphyry-type and gold mineralization. Information concerning specific properties and the general geology of the district is included in reports by Callaghan and Buddington (1938) and Brooks and Ramp (1968). In addition, Gray (1978) has provided a field guide and historical update to the area. Details of the geology and mineralization have been described by Lutton (1962) and more recently by Schaub (1978), and Tregaskis (1975) has studied the distribution of metals in samples of rock and stream sediment.

Geologic features of the Bohemia district are presented in Figure 26. The country rocks are predominantly volcanic tuffs, multilithic breccias, flows of andesite and basalt, and small plugs and flows of dacite, which Schaub (1978) has tentatively correlated with the Little Butte Volcanic Series of Oligocene to Miocene age.

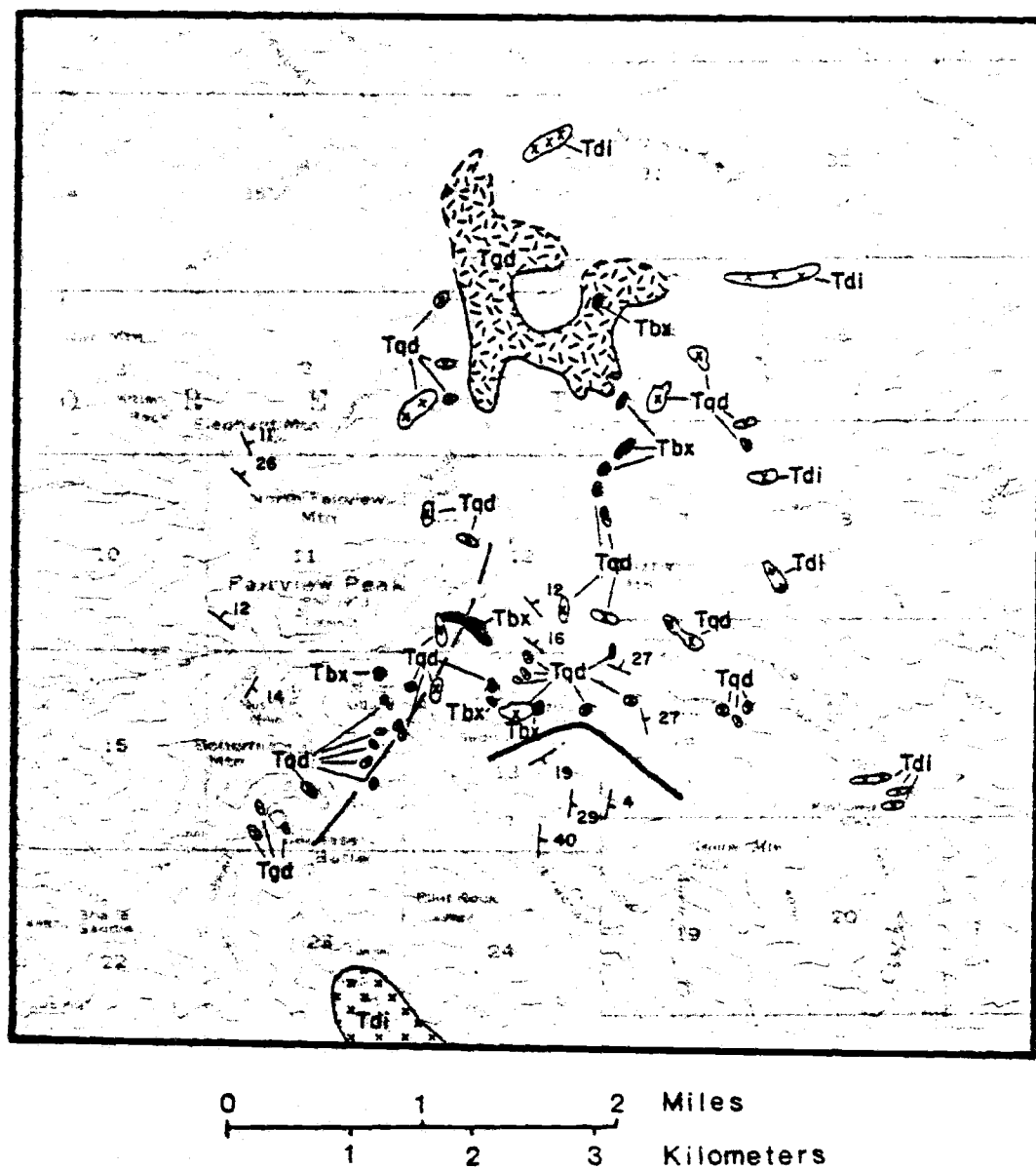


Figure 26. Geologic summary of the Bohemia District.

They are intruded by a large number of plutons of varying size and ranging from diorite to quartz monzonite in composition. The Champion stock, in the northern part of the district, is one of the larger plutons in the Western Cascades of Oregon. A broad, gently folded, northeast-trending anticline in the southern part of the district is the principal structure. Numerous small faults, having trends both to the northwest and to the northeast, are widespread and served as conduits to channel the later hydrothermal fluids.

The locations of breccia pipes, areas of alteration, veins, and the principal mines and prospects are illustrated in Figure 27. Mineralization is localized both in plutonic and volcanic host rocks. The ore-bearing minerals have been deposited chiefly as open-space cavity fillings. Most have formed mineralized veins and shear zones, but stockwork-type occurrences of the minerals along closely spaced veinlets and fractures are found at a few prospects. Disseminated sulfides are locally present in the breccia pipes and in the wall-rock adjacent to mineralized structures. The veins and shear zones are steeply dipping and the majority strike to the northwest or west, as do some dikes and elongate plugs and breccia pipes. Metallic constituents of the veins are principally zinc, lead, iron, and copper that are accompanied by small amounts of silver and gold. The sulfides are chiefly sphalerite, galena, pyrite, and chalcopyrite, but minor stibnite and tetrahedrite may be present locally. Common gangue minerals include quartz, carbonates, barite, clays, specular hematite, and sometimes adularia. The vein constituents range from

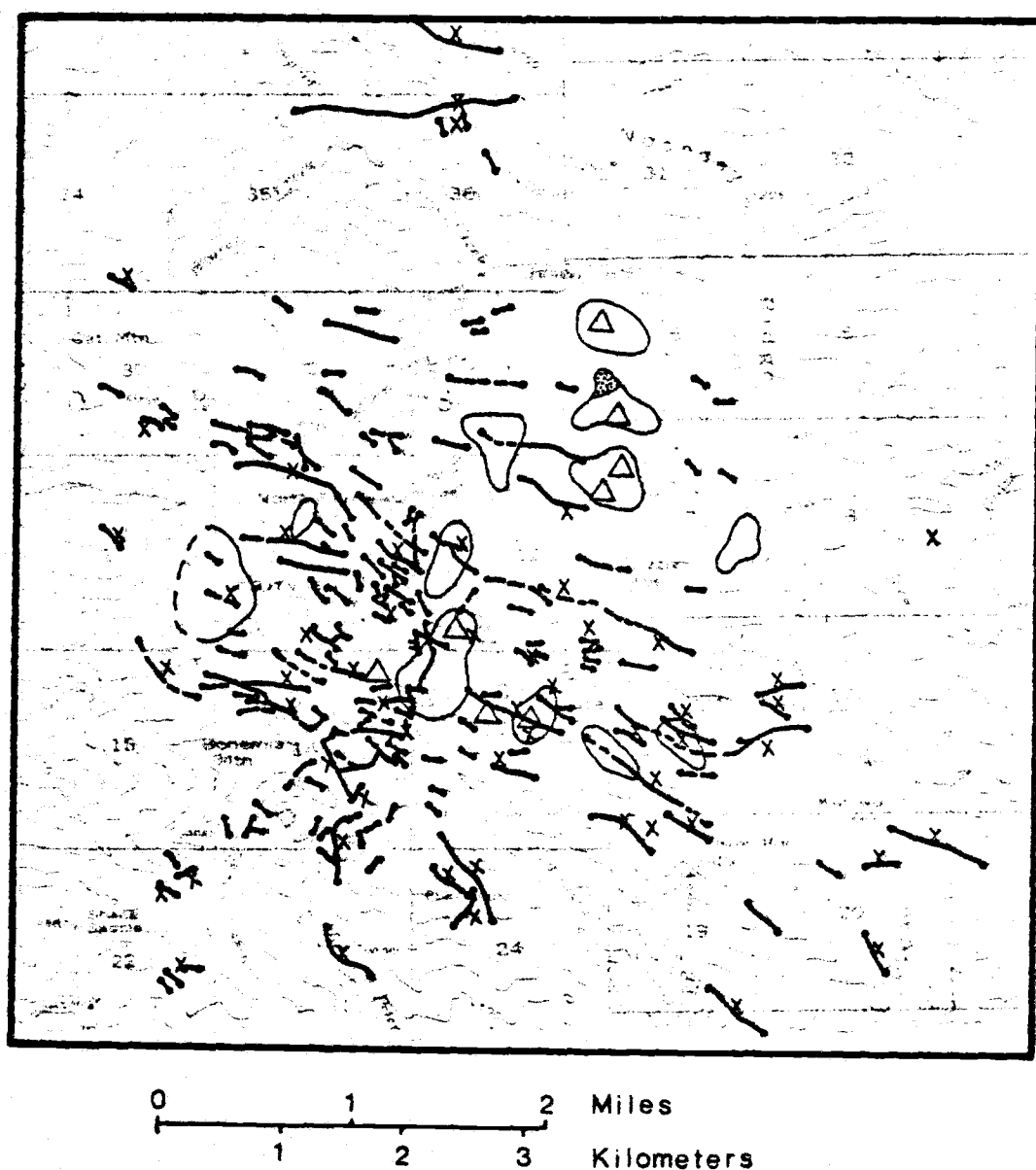


Figure 27. Mineralization summary of the Bohemia District.

coarsely crystalline to cryptocrystalline in size, and textures may be banded, vuggy, or brecciated. Minerals may be crustified in the banded parts of the veins, and the crusts may exhibit bilateral symmetry. According to Callaghan and Buddington (1938), the vein minerals are crudely zoned on a district-wide scale. Specular hematite is most abundant in the central part, whereas stibnite is found only in the periphery. Additionally, Schaubs (1978) has noted that the centrally located veins are characterized by the highest proportions of sulfide to gangue minerals and the largest ratios of galena/sphalerite and galena/chalcopyrite, and the host rocks of this terrain contain anomalously high concentrations of lead. Because some of these chemical and mineralogical trends are contrary to those expected from "ideal" hydrothermal zonations, they probably have been complicated by other effects imposed by paragenesis and topography.

Several tourmaline-bearing breccia pipes are present in the Bohemia district (Schaubs, 1978), and in most respects they are similar to those of the Washougal and North Santiam districts. The pipes are commonly light colored as a consequence of hydrothermal alteration. Fragments of country rock contained as clasts within these breccias are replaced by quartz, sericite, and tourmaline. Disseminations of pyrite, or stains of limonite indicative of the former presence of sulfides, are typical of these breccia pipes, and one (SW cor. sec. 6) contains unoxidized chalcopyrite.

Most of the plutonic and volcanic rocks of the Bohemia district have been hydrothermally altered to propylitic assemblages consisting

of albite, epidote, chlorite, quartz, carbonates, sericite, zeolites, magnetite, and pyrite. Locally, alteration is to higher intensities of the argillic-phyllic types that are dominated by quartz, sericite, kaolinite, and tourmaline. These are closely associated with the breccia pipes, especially the quartz-tourmaline assemblage, and they are also found as selvages in the wall rocks of some veins (see Fig. 27). Schaub (1978) noted potassic alteration in one small area along the south and southeast contacts of the Champion stock (south part of common boundary to secs. 1 and 6). It consists of potassium feldspar, occupying thin veinlets and forming replacements of plagioclase feldspar, that is accompanied by biotite and other alteration minerals. Coincident with this highest grade of alteration is a geochemical anomaly for copper and molybdenum (95 ppm Cu, 20 ppm Mo), and immediately to the southeast is the chalcopyrite-bearing breccia previously mentioned. This association of pluton, breccia pipe, potassic alteration, and geochemical anomaly is suggestive of nearby porphyry-type mineralization. Moreover, this terrain is also defined by the heaviest and most magmatic oxygen isotope values reported by Taylor (1971) for this district, which in turn may be indicative of a large intrusion and (or) root zone of a hydrothermal system at depth.

#### South Umpqua District

This "district", also known as the Zinc mine or prospect, is located in Douglas County, approximately 30 miles east-southeast of Roseburg, Oregon. Mineralization was discovered in 1910 and is mani-

fest in at least two distinct zones that extend over a small area of less than one square mile. Although exploration and property development have taken place periodically, there is no record of mineral production. Descriptions of the past mining activity, local geology, and prospects have been summarized by Callaghan and Buddington (1938), Oregon Department of Geology and Mineral Industries (1940), and Brooks and Ramp (1968). Additional details of the geology, petrology, and mineralization of this area have been described recently by Ness (1976).

Host rocks consist of an interbedded sequence of volcaniclastics and flows of basalt and andesite that belong to the Colestin Formation of Eocene age. They strike to the north and dip moderately to the east. These volcanic rocks have been intruded by numerous dikes of diabase and equigranular to porphyritic andesite and diorite. Most are narrow (less than one foot wide) and they exhibit finely crystalline to aphanitic textures. The largest is about 25 feet wide, composed of porphyritic quartz diorite, and is situated between the two main prospects. All dikes dip steeply and strike to the northwest.

Mineralization is primarily controlled by northwest-trending faults, fractures, and shear zones. Vein minerals localized as cavity fillings in the shear zones have been intensely fractured and (or) brecciated. The sulfides consist chiefly of pyrite and sphalerite that are accompanied by minor quantities of galena, chalcopyrite, and possibly marcasite. They are contained in a matrix of

crushed rock, calcite, clay minerals, and sometimes quartz. Plutonic and volcanic host rocks in the central part of the area contain small amounts of disseminated pyrite. Hydrothermal alteration is widespread, of generally weak intensity, and belongs exclusively to the propylitic type. It is characterized by albite, chlorite, epidote, secondary amphibole, clay minerals, quartz, calcite, sericite, magnetite, and pyrite. However, petrographic studies have revealed an unexpected alteration mineral in a sample of volcanoclastic andesite from the northern part of the district. Replacing this host are tiny microcrystalline "sunbursts" of tourmaline in addition to the usual propylitic minerals. Although visible mineralization consists only of the propylitic constituents and fracture-controlled veinlets of quartz and pyrite, this sample is also geochemically anomalous in copper and molybdenum (115 ppm Cu, 15 ppm Mo). The district does not appear to warrant a major exploration program on the basis of its size or geologic features, but the presence of tourmaline and copper-molybdenum anomaly suggests a larger hydrothermal system at depth, and one possibly analogous to those farther to the north.

#### Al Sarena and Barron Mines

Although this work does not extend beyond the South Umpqua district, a southward continuation of the Western Cascades metallogenic province is inferred on the basis of at least two isolated properties along this trend. These are the Al Sarena and Barron mines which are located about 16 miles southwest and 62 miles south,

respectively, of the South Umpqua district. Features they share in common with other mines of this province include volcanic host rocks of Tertiary age, proximity to nearby dike-like intrusions, and recovery of minor gold and silver. Information concerning these properties is entirely from reports by Callaghan and Buddington (1938), Brooks and Ramp (1968), and references cited therein.

The Al Sarena (Buzzard) mine is in northern Jackson County approximately 44 miles southeast of Roseburg, Oregon. It was discovered in 1897 on the basis of placer gold, and production of gold with minor silver and lead is valued at \$24,000 (see Table 3). Host rocks at the mine are Tertiary flows and volcanic breccias of rhyolite and andesite that have been intruded by dikes of similar composition. Brooks and Ramp (1968) indicate a northwest trend for nearby granitic dike(s). The mineralized vein structures are steeply dipping and strike to the northwest. They contain streaks, lenses, and veinlets of the sulfides in altered rock and fault gouge having minor quantities of finely crystalline silica. Sphalerite is the dominant sulfide, and it may be accompanied by smaller amounts of galena, pyrite, and traces of chalcopyrite and arsenopyrite. Host rocks in the vicinity of the mine, and particularly adjacent to the veins, are intensely altered and bleached, and contain disseminated pyrite. This alteration, at least locally, is presumably of the argillic-phyllic type.

The Barron mine is in southern Jackson County about 8 miles east-southeast of Ashland, Oregon. Although historical records are

incomplete, mineralization at this property is believed to have been recognized by 1883. The value of total production is estimated to be about \$9,000, and derived entirely from the precious metals (silver 25 times more abundant than gold). Country rocks are breccias of andesite and flows and dikes of basalt, andesite, and minor rhyolite. A northwest-trending dike of dacite porphyry crops out to the south of the mine. The property has two veins that also strike to the northwest. They are composed of altered rock, gouge, finely crystalline silica, calcite, and barite. Sphalerite, the most abundant sulfide, is associated with minor amounts of galena, chalcopyrite, pyrite, arsenopyrite, stibnite, realgar, and pyrargyrite. The sulfides are localized as fracture fillings, stringers, and veinlets within the vein structures. Host rocks adjacent to the veins have been altered to an argillic-phyllic assemblage consisting of sericite and clay minerals. Although not reported in the literature, it is presumed that propylitic alteration is widespread in the country rocks beyond the mineralized veins at both the Al Sarena and Barron mine areas.

## FEATURES OF EXPLORATION SIGNIFICANCE

In years past, the critical guide to an orebody was the surficial exposure of ore grade mineralization. Today, most outcrops of obvious mineralization have been discovered, except in the more remote parts of the world. Accordingly, exploration geologists have had to develop more sophisticated techniques for locating hidden or deeply buried "blind" orebodies. Modern exploration programs generally begin with the formulation of a geologic, or genetic, model for the type of mineral deposit that contains the desired metal commodities. Exploration is then directed to those regions having the appropriate geologic characteristics. The initial effort is guided by the available information and intuition that are further supplemented by reconnaissance geologic mapping and geochemical analyses of stream sediment samples. As exploration continues, smaller areas are defined on the basis of favorable criteria determined from comparisons to the genetic model, and the best of these are selected for more thorough examination by means of detailed geologic mapping, rock sample geochemistry, and commonly geophysical surveys. Areas in which the convergence of features indicate mineralization at depth or hidden nearby become the prime target areas that subsequently undergo evaluation by diamond drilling during the final stages of an exploration program.

The mining districts of the Western Cascades offer great promise for the discovery of porphyry-type copper and molybdenum

mineralization. These areas warrant detailed exploration because of the historical production of gold and silver from the base and precious metal-bearing veins and their coincident association with granitic plutons and large areas of propylitic hydrothermal alteration. Porphyry-type deposits are uniquely associated with the later porphyritic phases of shallow, hypabyssal intrusions of intermediate to silicic composition that have crystallized from calc-alkalic to alkalic magmas. For the purposes of exploration, especially in geologically young terrain such as the Western Cascades, the best evidence for the likely presence of these critical host rocks is the voluminous outpourings of compositionally similar volcanic rocks. Although they may serve as host rocks to ore, the volcanic rocks themselves do not constitute a direct guide to porphyry-type mineralization. Their presence merely serves to define areas or regions of igneous activity in which comagmatic intrusive equivalents may be found. Accordingly, the remainder of this chapter considers those features relevant to the exploration of hydrothermal deposits and it is specifically focused on those relating to known or probable occurrences of porphyry-type deposits in the Western Cascades of Oregon and southern Washington. These diagnostic features include the plutons, breccia pipes, ore and gangue minerals, distribution and types of hydrothermal alteration, the geochemistry of metals in the host rocks and mineral deposits, the sulfur isotopic composition of ore minerals, and the fluid inclusions contained in gangue minerals associated with ore.

## Plutons

The spatial and temporal association of porphyry-type deposits with plutons of intermediate to silicic composition that have been derived from the crystallization of calc-alkalic and alkalic magmas have been documented worldwide by numerous investigators. Evidence clearly suggests that the relationship between the hydrothermal fluids that formed these disseminated and fracture-controlled deposits of copper and molybdenum and fringing vein or replacement deposits of copper, zinc, lead, and silver-gold and the epizonal plutonic host rocks is genetic rather than coincidental. The near contemporaneity of the plutons and the associated hydrothermal minerals is well documented for the Cascade Range (see Tbl. 2), elsewhere throughout the Pacific Northwest (Field and others, 1974), and for many other metallogenic provinces of the world (Titley and Beane, 1981). Porphyry-type deposits, as previously noted, occupy the deep central core of plutonic-hydrothermal systems from which the metals and minerals are concentrically zoned both upward and outward. The importance of the aqueous component in these systems may be inferred from the invariably porphyritic and sometimes vesicular textures of the plutonic host rocks, and more directly from the coincident association with innumerable closely-spaced fractures (Burnham, 1979), breccia pipes (Norton and Cathles, 1973), hydrous products of host rock alteration, and the mineralogy and textures of the veins.

The source of metals and fluids may have been primarily from the plutonic magmas, as is suggested by some of the isotopic, structural, and textural evidence, or from adjacent country rocks saturated with connate or meteoric waters. Although this question is unresolved, the intimate association of plutons and hydrothermal mineral deposits is universal.

A summary of the characteristics of the plutons in the mining districts of the Western Cascades is present in Table 4. These plutons range in age from early to late Miocene (7 to 22 m.y.). The size of the plutons varies from small dikes and plugs to stocks. Most of these intrusions are porphyritic with a fine-grained groundmass. Plagioclase feldspar, augite, hornblende, and hypersthene are common phenocrysts and are set in a groundmass of the same minerals along with quartz and minor biotite and potassium feldspar. Quartz diorites and grandodiorites are the most common plutonic rock types. Granites, tonalites, diorites, quartz monzonites, and aplites are less abundant.

The largest plutons within a given district are generally found at lower elevations. The largest, most complex plutons are found at lower elevations in the Washougal and North Santiam districts. These plutons are not homogeneous, but are intrusive complexes composed of a variety of plutonic phases which are distinguished using textural, mineralogical, and chemical criteria. The plutons within these two districts, are generally smaller and less complex with increasing altitude. This variation in plutonic size and complexity with

Table 4. Characteristics of plutons in mining districts of the Western Cascades

	<u>Washougal</u>	<u>N. Santiam</u>	<u>Detroit Dam</u>	<u>Quartzville</u>	<u>Blue River</u>	<u>Bohemia</u>	<u>S. Umpqua</u>
Host	Ohanapecosh Fm. (Eocene-Oligocene)	Sardine Fm. (Miocene)	Sardine Fm. (Miocene)	Sardine Fm. (Miocene)	Sardine Fm. (Miocene)	Little Butte Volc. Ser. (Oligocene-Miocene)	Colestin Fm. (Eocene)
Age (m.y.)	20	13	7	?	13	22	?
Area (mi <sup>2</sup> )	~ 23	~ 1	~ 4	< 0.5	< 0.2	< 1	< 0.1
Altitude (ft)	1000-4050	1900-3750	1200-3800	1450-4100	2600-4400	2200-5500	1400-1600
Form	composite stock with tongues; satellitic plugs and dikes	stock with satellitic plugs and dikes	stock with satellitic plugs and dikes	plugs, dikes, and sills	plugs and dikes	stock with satellitic plugs and dikes	dikes
Phases	aplite granodiorite* qtz. diorite* granodiorite qtz. diorite diorite	aplite granodiorite* diorite microdiorite*	aplite granodiorite*	aplite qtz. monzonite* granodiorite* qtz. diorite* diorite*	granodiorite* qtz. diorite* diorite*	aplite granodiorite* qtz. diorite* granodiorite	qtz. diorite*

\*designates porphyry or porphyritic phases

List of plutonic phases does not include those of chiefly mafic to intermediate compositions that occupy plugs, dikes, and sills in the country rocks and are interpreted to be probable feeders to the volcanic sequence.

elevation may indicate that larger composite plutons underlie other districts in the Western Cascades. Indeed, stocks are exposed at lower elevations in the Bohemia and Quartzville districts and in the Detroit Dam area.

In the Washougal and North Santiam districts, certain late plutonic phases seem to be more closely related to mineralization. Olson (1978) reported evidence which indicates a genetic relationship between the Hewlit granodiorite and metallization. Disseminated mineralization occurs as a halo around the largest granodiorite pluton and vein metals are zoned around this intrusion with the more mobile elements at greater distances from the pluton. In the Washougal district, Schriener (1978) noted that granodiorite porphyry and quartz diorite porphyry were the phases most closely associated in space and time with breccia pipe formation and mineralization. In the southern part of the stock, the quartz diorite porphyry contains anomalous amounts of copper and is vesicular indicating a possible genetic relationship to hydrothermal activity (Shepard, 1979). Birk (1980) found that a copper-bearing breccia pipe is associated with the granodiorite porphyry phase of the Silver Star stock, whereas the "barren" pyrite-bearing breccias are associated with the earlier quartz diorite porphyry.

In other districts of the Western Cascades, direct associations between mineralization and specific plutonic phases are not readily apparent. Plutons are smaller, and mineralization is limited to sporadic vein-type mineralization. In addition, although the

mineralogy and textures of the plutons are variable, distinct plutonic phases are not readily distinguished without the aid of chemical analysis. The preponderance of vein-type mineralization and the small size of the plutons indicate that these districts represent higher levels in the plutonic-hydrothermal system.

As indicated in an earlier chapter, plutonic rocks of the Western Cascades are chemically similar to plutons associated with porphyry deposits from island arc terranes in the Guichon Creek Batholith of south central British Columbia, and the Caribbean. Unfortunately, unless porphyry metallization is exposed, criteria to distinguish between barren and mineralized plutons cannot be established. Pyroxene is rare, or virtually absent in porphyritic intrusions related to copper mineralization, whereas hornblende and biotite are more common (Titley and Beane, 1981). In the Western Cascades, pyroxene is conspicuous in most intrusions. However, all of the districts have at least one intrusion in which hornblende and (or) biotite are the predominating ferromagnesian minerals. Feiss (1978) has devised a plot of  $\text{SiO}_2$  versus  $\text{Al}_2\text{O}_3/\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}$  to distinguish mineralized and unmineralized plutons within the Caribbean porphyry province. According to this scheme, plutons having a high  $\text{Al}_2\text{O}_3/\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}$  ratio should have the potential for porphyry copper mineralization. For magmas deficient in  $\text{Al}_2\text{O}_3$ , copper should enter the octahedral sites of early formed crystals and will not be available for inclusion in late stage hydrothermal fluids. However, if the initial magma contains insufficient quantities of copper,

porphyry mineralization is unlikely to occur regardless of  $\text{Al}_2\text{O}_3$  content. Unfortunately, these results were not applicable to porphyry deposits in the southwestern Pacific where there is considerable overlap of the  $\text{Al}_2\text{O}_3/\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO}$  ratios for mineralized and unmineralized plutons (Mason and Feiss, 1979). Thus, the  $\text{Al}_2\text{O}_3/\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO}$  ratios are useful only in specific metallogenic provinces in which data for productive and non-productive plutons are available. Perhaps the most important feature in distinguishing productive plutons is the degree of fracturing (Titley and Beane, 1981). In the districts of the Western Cascades, most plutons and volcanic host rocks have been extensively fractured and subjected to pervasive hydrothermal alteration.

Evidence such as the association of porphyry-type mineralization with composite plutons of intermediate composition in the North Santiam and Washougal districts, the chemical and mineralogical similarities between high level plutons in these districts with the small plutons found in other districts in the Western Cascades and with mineralized plutons elsewhere in the world, and the common presence of intensely fractured plutons and volcanic host rocks throughout the terrain, collectively attest to the likely potential for porphyry-type mineralization at depth in other districts of the Western Cascades.

## Breccia Pipes

Intrusive breccias are frequent associates of epizonal plutons, and are common throughout the circum-Pacific region. These breccias are often in the form of elongate, chimney-like masses, which are subcircular to elliptical in plan. Such breccia pipes, as they are called, are commonly mineralized, and in many mining districts are closely associated with high grade mineralization. Accordingly, they are a valuable guide to exploration (Perry, 1961; Field and others, 1974; Gilmour, 1977). Breccia pipes are associated with mineralization in porphyry deposits in the southwestern United States (Lowell and Guilbert, 1970; Gilmour, 1977), in British Columbia, Canada (Field and others, 1974; Seraphim and Hollister, 1976), northern Mexico (Perry, 1961), in the South American Cordillera (Richards and Courtwright, 1958; Howell and Molloy, 1960; Sillitoe and Sawkins, 1971; and Gustafson and Hunt, 1975), and in the southwest Pacific islands (Gustafson, 1978).

Breccia pipes are closely associated with late stage porphyry intrusions and are formed as a result of the process of solidification of a hydrous magma in a shallow subvolcanic environment. However, the actual mechanism of breccia pipe formation has been a subject of controversy for many years. An early theory is that of fluidization (Reynolds, 1954), a process in which a magmatic fluid phase escapes and moves upward rapidly as a result of a high pressure gradient formed by venting at the surface. Reynolds (1954) has suggested that clasts and comminuted material could be suspended

in and carried along by this fluid phase. Recent studies indicate that fluidization is probably not a significant mechanism in the formation of breccia pipes (Wolfe, 1980). A more favored hypothesis involves the creation of a pre-breccia void as a result of host rock dissolution by corrosive hydrothermal fluids, which have evolved from a solidifying magma (Sillitoe and Sawkins, 1971). The walls of the void thus created would collapse and spall inward to create a breccia. Perry (1961) has suggested that fluctuations in magma pressure are the cause of fracturing of host rock and subsequent creation of an open space into which rock may fall to form a breccia. More recently, Norton and Cathles (1973) have proposed that a pre-breccia void could result from the entrapment of vapor in the cupola of an intrusion. Increasing vapor pressure with progressive crystallization and cooling of the intrusion would eventually result in the explosive piercement of the rind (Burnham, 1979) and the formation of a breccia. Yet another hypothesis proposes that the breccias are formed during phreatomagmatic explosions resulting from the interaction of ground water and ascending magma (Wolfe, 1980). Fragments of such breccias might be characterized by rounded to subrounded shapes ranging from microns to meters in size. Currently, the Norton and Cathles model is the most favored, although elements from these several hypotheses may play a role in the formation of these scientifically interesting and sometimes economically significant structures.

Breccia pipes are spatially associated with epizonal plutons and porphyry-type mineralization throughout the Cascades, and they have been reported to be in close proximity to the Cloudy Pass batholith/prospects near the Glacier Peak porphyry deposit (Cater, 1969; Grant, 1969), Vesper Peak stock/Sunrise prospect (Grant, 1969; Hedderly-Smith, 1975), the Snoqualmie batholith/Middle Fork prospect (Grant, 1969; Patton and others, 1973). Breccia pipes are also found in the Washougal, North Santiam, Quartzville, and Bohemia districts of the Western Cascades. They range from 3 to 100 meters in diameter. In some areas, groups of breccia pipes are aligned along a trend which may coincide with that of the longest horizontal axis of the breccia pipe (Olson, 1978). Host rocks for the breccias may be volcanic or plutonic, but the pipes are always in close proximity to an intrusion. Alteration halos surround the breccia pipes and commonly may obscure contact relationships with the enclosing country rock. Contacts, where observed, are usually gradational from breccia outward to fractured country rock.

Breccias are usually composed of irregular fragments of altered country rock. These clasts normally range from one millimeter to five centimeters in diameter. They are usually angular to sub-rounded, and often lath-shaped. Fragments may be surrounded by a matrix of smaller rock particles and rock flour, or by a cement of quartz, tourmaline, and sericite. Void spaces are common in these breccias. Clasts may sometimes be free-floating in these voids, and uncemented to surrounding fragments.

The hydrothermal mineral assemblage in most breccia pipes of the Western Cascades is relatively simple: it consists of quartz, sericite, and tourmaline in variable proportions. The absolute abundances and relative proportions of these minerals vary greatly in different pipes and at different locations within a single pipe. Tourmaline is most commonly present as disseminated needles and starbursts. It may replace rock and mineral fragments and (or) form a cement. Schorlite is the most common type of tourmaline found in the Western Cascade pipes. Birk (1980) has recently completed detailed studies of tourmaline in some breccia pipes of the Washougal district, and has recognized two distinct populations of tourmaline. They are represented by alumina-rich and iron-rich varieties of schorl. Paragenetic relationships indicate that these two types represent different stages of hydrothermal activity. The alumina-rich variety is associated with pyrite-bearing breccias and formed earlier than the iron-rich type which is associated with chalcopyrite. A similar relationship may exist in other districts as well. Preliminary studies by Olson (1978) and Schaub (1978) indicate that more than one stage of tourmalinization took place in the breccias of the North Santiam and Bohemia districts. The relative abundance of tourmaline decreases with increasing altitude both throughout entire districts and within individual breccia pipes. Those from the southern part of the Washougal district do not contain tourmaline (Shepard, 1979). They intrude volcanic rocks at generally higher elevations than most of their tourmaline-bearing counterparts in the

northern part of that district which usually intrude plutonic rocks. Schaub (1978) also found that tourmaline is less abundant in higher levels of the breccias of the Bohemia district.

Microcrystalline sericite and quartz commonly replace the fragments of breccia pipes. Coarser sericite sometimes rims tourmaline crystals. Quartz is present not only as an early replacement mineral, but also as a late-stage mineral in vugs and veinlets. Breccia pipes in the southern part of the Washougal district are composed almost entirely of quartz, sericite, and rock flour (Shepard, 1979).

Although most breccia pipes are simple in mineralogy, a few contain other minerals in variable amounts. Some breccia pipes contain minor, or rarely major, amounts of magnetite, hematite, pyrite, chalcopryrite, and (or) bornite. According to Schriener (1978), chalcopryrite comprises up to 50 percent of the matrix of the Miners Queen breccia pipe in the Washougal district. In other breccia pipes, the former presence of sulfides is indicated by limonite stains. Potassium feldspar is an important constituent in some of the pipes in the North Santiam district (Olson, 1978). In the Washougal district, actinolite is common in some breccias (Schriener, 1978). Minor amounts of epidote, chlorite, biotite, clays, and sphene are also found in some pipes. Shepard (1979) has described a zone of propylitized breccia in the southern part of the Washougal district.

Three types of breccia pipes have been described in the Western Cascades based on the criteria of fragment shape, ratio of matrix to fragments, and the extent of fragment displacement. These three types are matrix-rich breccias, rubble-rich breccias, and shatter breccias. Matrix-rich breccias have been described in the Washougal and Bohemia districts. The clasts in these breccias appear to be suspended in a matrix of quartz, rock flour, sericite, and commonly tourmaline. Fragments are angular to subrounded and vary greatly in size. They may be in subparallel alignment near the contacts of the pipe with the country rock. In fact, Schriener (1978) has found that this type of breccia often grades outward into rubble-rich breccia. These pipes may exhibit up to 35 meters of relief in the Washougal district because they have been silicified and thus are resistant to erosion. According to Birk (1980), tourmaline from a matrix-rich breccia in the Washougal district is of the alumina-rich variety associated with pyrite.

Rubble-rich breccias are found in the Washougal, North Santiam, Quartzville, and Bohemia districts. These breccias consist of angular and lath-shaped fragments of fairly uniform size. The clasts are commonly in subparallel alignment and display evidence of both translational and rotational movement; that is, some fragments have a "jigsaw puzzle" fit, whereas others do not have an obvious relationship to nearby fragments. Interfragmental voids are common, and may comprise up to 15 percent of the rock (Olson, 1978). Rock flour is not a common constituent of these breccias. Muntz (1978) and Olson

(1978) have suggested that more than one episode of brecciation may have taken place in these pipes; many fragments show textural evidence of prior brecciation and cementation. Rubble-rich breccias commonly grade outward into shatter breccias. Mineralization is commonly associated with rubble-rich breccias. Those of the Washougal and North Santiam districts contain chalcopyrite and bornite, whereas breccia pipes of the Bohemia district are chiefly pyrite-bearing.

Shatter breccias consist of highly fractured rock in which little or no separation of fragments has taken place. These breccias, in the Washougal district, occupy zones that surround other types of breccias. Several pipes of shatter breccia have been described in the North Santiam and Bohemia districts. Schaub (1978) has suggested that these pipes represent a higher level of emplacement, or the upward or outward termination of other types of breccia pipes.

In addition to these three major types of breccia pipes, dikes and zones of breccia have been described in the Quartzville (Munts, 1978) and Washougal districts (Shepard, 1979). Breccia dikes of the Quartzville district form elongate zones of matrix-rich breccia that contain fragments of pyritized and silicified country rock with minor amounts of tourmaline. Their elongate distribution, tabular shape, and unidirectional internal structure suggest that they are probably related to fault zones.

Variations in the textures of breccias from the Western Cascades suggest that the pipes formed under similar, but not identical conditions. Textural features of the rubble-rich breccias, such as the "jigsaw puzzle" fit of many fragments, the absence of abundant rock flour, and the outward gradation to shatter breccias, suggest formation by solution stoping (Sillitoe and Sawkins, 1971), by vapor entrapment (Norton and Cathles, 1973), or by a combination of these two processes. Early solution vugs and pre-breccia alteration of fragments contained in these pipes suggest that solution stoping may have been an important process in their formation. The rounded fragments and abundant rock flour of the matrix-rich breccias may be the result of a more explosive process, and may have involved phreatomagmatic activity or fluidization.

#### Ore and Gangue Minerals

Many of the porphyry copper districts in the Western Cordillera were originally discovered on the basis of placer gold found in nearby stream beds. Prospectors in search of the "mother lode" usually discovered base metal veins and replacement deposits containing copper, lead, and zinc, in addition to gold and silver. These discoveries sustained the district after most of the placer gold had been recovered. Finally, the value of large tonnage, low grade disseminated mineralization was subsequently recognized and mining began on the porphyry deposits. Interestingly, the evolution of prospecting and mining in porphyry copper districts is consistent

with the metal and mineral zoning "discovered" by economic geologists in the last 20 years. Porphyry mineralization is usually central to a district and consists of chalcopyrite, bornite, and (or) molybdenite which are present as finely disseminated replacements and fillings of thin fractures and veinlets. Commonly a halo of disseminated pyrite surrounds the ore grade mineralization. Also outward from the porphyry-type mineralization are polymetallic veins which contain copper, lead, zinc, gold, and (or) silver. These metals may be zoned on a district-wide basis with copper and molybdenum commonly concentrated in the center of the district, and lead and precious metals more abundant in peripheral veins. Erosion of these peripheral veins and the porphyry mineralization itself results in the deposition of placer gold in nearby streams.

Mineral deposits in the Western Cascades consist of both base metal veins and disseminated pyrite and chalcopyrite mineralization. The discovery of most of these districts was based on occurrences of placer gold found in nearby stream gravels. Mining to date has been largely restricted to these placers and to oxidized portions of the veins, as unweathered parts of veins contain only trace amounts of gold and silver. Most of the veins strike northwesterly and westerly and dip steeply. They range in size from a few centimeters to over 15 meters in width, although they are commonly less than 50 centimeters wide. The largest and most persistent veins are found in the Bohemia district. Sphalerite, galena, chalcopyrite, and pyrite are the most abundant sulfides and quartz is the most common gangue

mineral. The relative amounts of these minerals varies greatly from vein to vein and from district to district. The hypogene ore, gangue, and alteration minerals in each district are presented in Table 5.

Most veins consist of brecciated country rock cemented with comb or drusy quartz. They are usually enclosed by altered rock which may contain disseminated pyrite. The products of hydrothermal mineralization are commonly crustified. The different mineral assemblages are duplicated (paired) on both walls of the vein and represent successive pulses of deposition. Surface exposures of the veins exhibit porous cellular textures and are stained with limonite indicating the former presence of sulfides.

Gold is seen only in weathered portions of the veins as flakes, wires, and dendritic growths. However, assays of unweathered vein material indicate that gold is present at depth, but in smaller amounts. Sphalerite is the most abundant zinc-bearing mineral and usually is present as light yellow-green to yellow-orange to black irregular masses. Black and yellow varieties are commonly found in the same vein. Galena is the dominant lead mineral, and it is normally associated with sphalerite and chalcopryrite. Chalcopryrite is the principal copper mineral and is found as small anhedral and irregular masses. Tetrahedrite is a minor component of the veins. Bornite is common in the veins of the Washougal district and in some breccia pipes of the North Santiam district. Products of chemical weathering of the copper minerals include chalcocite, covellite,

Table 5. Hypogene ore, gangue, and alteration minerals of veins and host rocks  
in mining districts of the Western Cascades

	Washougal	N. Santiam	Detroit Dam	Quartzville	Blue River	Bohemia	S. Umpqua
Ore	bornite chalcopryrite galena gold magnetite molybdenite pyrite pyrrhotite sphalerite	bornite chalcopryrite galena gold hematite magnetite molybdenite pyrite sphalerite	chalcopryrite galena pyrite sphalerite	bornite bournonite chalcopryrite galena gold pyrite sphalerite stibnite tetrahedrite	chalcopryrite galena gold pyrite sphalerite tetrahedrite	chalcopryrite galena gold hematite magnetite marcasite pyrite sphalerite stibnite tetrahedrite	chalcopryrite galena marcasite pyrite sphalerite
Gangue	actinolite calcite epidote quartz tourmaline	adularia anhydrite ankerite barite calcite chlorite epidote fluorite quartz tourmaline	calcite quartz	ankerite barite calcite quartz tourmaline	adularia barite calcite quartz	adularia barite calcite dolomite hematite quartz tourmaline	calcite quartz
Alteration	actinolite albite biotite calcite chlorite clays epidote hematite magnetite orthoclase pyrite quartz sericite tourmaline uralite zeolite	albite biotite calcite chlorite clays epidote magnetite orthoclase pyrite quartz sericite sphene tourmaline	calcite chlorite clays epidote magnetite pyrite quartz sericite	alunite calcite chlorite clays epidote magnetite pyrite quartz sericite tourmaline zeolite	albite calcite chlorite clays epidote magnetite pyrite quartz sericite zeolite	albite biotite calcite chlorite clays epidote magnetite orthoclase pyrite quartz sericite tourmaline zeolite	albite calcite chlorite clays epidote magnetite pyrite quartz sericite tourmaline uralite
Alteration types	potassic argillic- phyllitic propylitic	potassic argillic- phyllitic propylitic	propylitic	argillic- phyllitic propylitic	argillic- phyllitic propylitic	potassic argillic- phyllitic propylitic	propylitic

chrysocolla, and minor azurite and malachite. Rugged topography and abundant rainfall increase the importance of mechanical weathering; thus, these secondary minerals rarely accumulate in significant amounts. Pyrite is the most abundant sulfide mineral. It is common in veins and in the nearby country rocks and it usually forms small anhedral and cubic euhedra. Veins and breccia pipes near the center of some districts contain specular hematite. Magnetite is common in veinlets, breccia pipes, and in altered rocks, but is relatively uncommon in the larger veins. Stibnite is found only in peripheral veins of the Bohemia and Quartzville districts and at the Barron mine. In addition, small quantities of arsenopyrite, realgar, and pyrargyrite are present locally in small veins of the southernmost Al Sarena and Barron mines.

Quartz is the most abundant gangue mineral. Its distribution is widespread and texture highly varied. The quartz may be present as large terminated crystals which line vugs, as a filling of veinlets that exhibit comb textures, and as cherty masses having colloform structures. It is the sole constituent of a few massive silica veins in the Quartzville district. Calcite is a common gangue mineral, especially in peripheral veins. Other gangue minerals include barite, dolomite, ankerite, adularia, johannsenite, epidote, sericite, chlorite, tourmaline and clay minerals.

Callahan and Buddington (1938) classified the veins into five groups. The most common type is a complex sulfide vein containing sphalerite with lesser amounts of pyrite, galena, and chalcopyrite

that are enclosed in a gangue of quartz and altered country rock. Gold and silver values are low except in the weathered portions of the veins. Chalcopyrite-dominated veins also have low contents of gold and silver, and are found in the Bohemia, Washougal, and North Santiam districts. Gold-quartz veins are most common in the Quartzville district. Carbonate veins are usually peripheral to most of the mineralization, but they have yielded several thousand dollars in gold. Veins of cherty quartz containing stibnite and pyrite are found in the peripheral fringes of the Bohemia and Quartzville districts.

A rough areal zonation of vein minerals has been observed in the Bohemia and North Santiam districts (Callahan and Buddington, 1938). Veins in the central part of the Bohemia district are larger, more continuous, and contain more sulfides relative to those of the periphery. Also, the galena to sphalerite ratios are highest in the central part of the district (Schaubs, 1978). Veins of quartz-stibnite are found at the margins of this district. The North Santiam district has a central zone characterized by chalcopyrite and specularite, an intermediate zone dominated by chalcopyrite and pyrite, and an outer zone containing mainly sphalerite and galena (Olson, 1978). Calcite becomes increasingly more abundant in veins outward from the center of the district.

Disseminated sulfide mineralization has been reported in the Washougal, North Santiam, and Quartzville districts. In the North Santiam district, pyrite and chalcopyrite are present in microvein-

lets and as disseminated replacement blebs accompanied by trace amounts of bornite and molybdenite. These sulfides replace ferromagnesian minerals of the microdiorite host. Associated gangue minerals include quartz, calcite, and occasionally traces of barite, anhydrite, and fluorite in the North Santiam district. In the northern part of the Washougal district, disseminated mineralization is associated with the Black Jack and Miners Queen breccia pipes. Chalcopyrite, bornite, magnetite, pyrrhotite, and molybdenite are intergrown with a gangue of tourmaline, biotite, amphibole, orthoclase, sericite, and quartz. Disseminated pyrite and sparse grains of chalcopyrite are found in the Dry Gulch area of the Quartzville district. In addition, Muntz (1978) has reported disseminated gold mineralization in a rhyodacite volcanic unit of this district.

Base and precious metal-bearing veins are normally peripheral to porphyry copper-molybdenum mineralization. The presence of these veins in conjunction with disseminated porphyry-type mineralization in the Washougal and North Santiam districts demonstrates that the Western Cascades is potentially a major province for porphyry copper-molybdenum mineralization. Mineral deposits in this region are directly related to the epizonal plutons, which served as a source of heat, and possibly of metals, sulfur, and water, to the hydrothermal solutions. This relationship is indicated in the North Santiam district by the direct association of disseminated mineralization with the large granodiorite intrusion and by the zonations of vein minerals and metals away from the central pluton. Although such

zonations of minerals and metals are not as apparent in the other districts, the presence of similar vein types, tourmaline-bearing breccia pipes, and evidence of disseminated mineralization suggests that porphyry-type deposits may underlie other mining districts of the Western Cascades.

### Hydrothermal Alteration

Studies of hydrothermal alteration and especially the spatial distribution of several mineral assemblages have been significantly relevant to the exploration for ore deposits, as well as to basic knowledge of hydrothermal processes. The principal types of alteration assemblages and their importance have been discussed previously. In brief, the interaction of hydrothermal fluids with enclosing country rocks results in the formation of new minerals and assemblages, which are determined by the chemistry-mineralogy of the host rock, composition of the fluids, and the temperature and pressure of fluid-rock reactions. The alteration assemblages are normally zoned both laterally and vertically as a result of chemical and thermal gradients in the hydrothermal system. Although the types and distribution of these assemblages are generally similar for most porphyry-type deposits, they may differ slightly in detail from one deposit to another. Nonetheless, four major types or assemblages are commonly recognized. Potassic alteration, characterized by the presence of biotite and (or) potassium feldspar in association with sulfides of copper and molybdenum, forms a deep central alteration

core in most districts. It is usually surrounded and embayed by irregular zones of phyllic and (or) argillic alteration, which may be partly later in age than the central potassic core. The phyllic zone is characterized by abundant sericite, whereas the argillic zone contains kaolinite and (or) montmorillonite. Rose and Burt (1979) have suggested that the kaolinite, and possibly the montmorillonite and sericite, may form as the result of decomposition of higher temperature alteration minerals as the hydrothermal system cooled and was subjected to processes of supergene weathering. Outward from the zones of potassic, phyllic, and argillic alteration is a large area of propylitization containing chlorite, calcite, albite, and (or) epidote. This propylitic fringe usually grades imperceptibly into "fresh" unaltered country rock. A quartz-tourmaline assemblage is also recognized in the Western Cascades (Schriener, 1978). It is most commonly found in association with breccia pipes of the Washougal, North Santiam, and Bohemia districts. However, only in the Washougal district is this type of alteration sufficiently extensive to warrant being mapped as a distinct assemblage (see Figure 18). Alteration minerals and alteration types found in each of the districts of the Western Cascades are listed in Table 5.

Propylitic alteration is the most widespread evidence of hydrothermal activity in the Western Cascades. Large halos of propylitic alteration surround the intermediate intrusions and all known occurrences of base and precious metal-bearing veins. Characteristic minerals include chlorite, epidote, calcite, albite, quartz,

sericite, magnetite, pyrite, uraillite and zeolites. The relative percentages of these minerals varies widely between and within districts. Ferromagnesian minerals are commonly replaced by chlorite, magnetite, green clays (montmorillonite?), and epidote. Plagioclase feldspar is replaced by sericite, calcite, albite, and epidote. Secondary quartz is commonly present in the groundmass of propylitically altered rocks, and it is also variably associated with the other alteration types as well. Pyrite, as tiny sparse disseminations or as a minor component of small quartz veins, is not uncommon. Zeolites and calcite are usually found in voids and coating fractures. Although propylitization changes the original mineralogy of these rocks, the intensity of this alteration is rarely sufficient to obliterate primary textures of the host rock as is often the case with argillic and phyllic types of alteration. Determination of the chemical effects of propylitic alteration on rocks of the Western Cascades is difficult because unaltered equivalents of most of the plutonic rocks are unavailable. However, significant changes in whole rock chemistry other than the introduction of minor  $H^+$  and  $CO_2$  are uncommon in propylitized rocks elsewhere (Titley and Beane, 1981 and references cited therein) and thus, are unlikely in the Western Cascades.

The mineral assemblage resulting from propylitic alteration is essentially identical to that produced by late magmatic (deuteric) alteration and by low grade regional (greenschist) and contact (albite-epidote hornfels) metamorphism. However, there is much

evidence to indicate that alteration in the Western Cascades resulted from hydrothermal processes. For example, stable oxygen isotope studies by Taylor (1971) have indicated that the solutions responsible for the alteration were hot meteoric groundwaters (hydrothermal) rather than magmatic waters. Propylitic alteration has affected both volcanic and plutonic rock types, although porous volcanoclastic rocks and fractured plutons are more susceptible to alteration than are dense volcanic flow rocks. Quartz veins and veinlets are found throughout the propylitized areas, as are the associated base and precious metal-bearing veins, and they provide good geologic evidence that suggests the hydrothermal solutions produced this alteration type. Propylitization is associated with more intense phyllic/argillic alteration (for example, immediately adjacent to the area of phyllic/argillic alteration associated with the large shear zone in the Blue River district, Fig. 25). However, its intensity is not directly related to the proximity to intrusions as would be the case for albite-epidote hornfels. According to Hartman (1973), the presence of chlorite, albite, epidote, quartz, calcite, mica (sericite?), clay minerals and zeolites in Tertiary volcanic rocks at Mt. Rainier resulted from elevated thermal gradients and convecting groundwater rather than regional metamorphism. There is little evidence to indicate that the intensity and extent of this alteration type increases with depth, as would be the case had regional metamorphism been the cause of this assemblage. However, the importance of heated meteoric waters in the

evolution of propylitic alteration is also supported by the fact that this assemblage is less widespread around the Glacier Peak (Rose, 1964), Margaret (R. A. Metz, 1981, personal communication) and Middle Fork (Patton and others, 1973) porphyry deposits in Washington, which implies that propylitization is most widespread in those mineralized areas of the Cascades that have been subjected to the least amount of erosion.

More intense types of argillic, phyllic, and potassic alteration are strongly controlled by structure in mineralized areas of the Cascades. As a consequence, the large areas of propylitic alteration in the Western Cascades are crosscut by zones of more intensely altered wall rock associated with veins, shears, breccia pipes, and faults. In the Glacier Peak and Margaret deposits, large blocks of unfractured and unaltered rock may be surrounded by intensely altered and mineralized ore in the phyllic and potassic zones.

The distinction between argillic and phyllic alteration is not clear in most districts of the Western Cascades because of the finely crystalline texture of these two assemblages. However, concentric zones of phyllic and argillic alteration have been reported by Muntz (1978) in the Quartzville district (see Fig. 23). The central phyllic zone is dominated by sericite and quartz associated with minor pyrite and clay minerals. A narrow, and gradational zone of argillic alteration surrounds this center. It is characterized by the presence of clay minerals and alunite (?), although the inner part also contains residual sericite and quartz. Outward, sericite

and quartz decrease in abundance as epidote and chlorite become the dominant phases.

Zones of locally intense argillic/phyllic alteration are common and are usually centrally positioned in the Washougal, North Santiam, Blue River, and Bohemia districts (see Figs. 18, 20, 25, and 27). This is most commonly associated with shear zones, faults, some breccia pipes, and large veins. The primary textures of the rock are commonly obscured by alteration to a finely crystalline mixture of quartz, sericite, kaolinite, and infrequently tourmaline. Limonite may be abundant and widespread, and indicative of the former presence of pyrite which may be observed in some outcrops. The weathering and oxidation of pyrite evolves acid solutions, which subsequently may produce alunite, kaolinite, and sericite from feldspars in a supergene environment (Rose, 1970). Probably most phyllic/argillic alteration in the Western Cascades is the result of both supergene and hypogene processes.

Changes in whole rock chemistry resulting from phyllic/argillic alteration can be dramatic. Typical effects of phyllic alteration include the removal of Na, Ca, and Mg whereas argillized rocks are extensively leached of all alkali cations. Major oxide analyses of two samples of a silicic dike from the Blue River district (BR-3 and BR-3X, Appendix 3) demonstrate the most extreme effects of phyllic/argillic alteration. Increases in  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{K}_2\text{O}$ , and decreases in  $\text{Fe}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ , and  $\text{Na}_2\text{O}$  have resulted from hydrothermally imposed changes in mineralogy. Propylitized samples

of the dike contain plagioclase, quartz, chlorite, carbonate and iron-titanium oxides whereas the more intensely altered sample contains only quartz, sericite, and clays. In the Washougal district, Schriener (1978) has reported increases in  $\text{SiO}_2$ ,  $\text{FeO}_t$ , and  $\text{K}_2\text{O}$ , and decreases in  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{CaO}$ , and  $\text{Na}_2\text{O}$  resulting from phyllic alteration. Olson (1978) noted additions of  $\text{TiO}_2$  and  $\text{K}_2\text{O}$  and removal of some  $\text{CaO}$  and  $\text{Na}_2\text{O}$  in the phyllic alteration of volcanic rock in the North Santiam district. Samples from the phyllic zone of the Margaret deposit (Appendix 5, Table 22) exhibit increases in the content of  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Na}_2\text{O}$ , and decreases in  $\text{Fe}_2\text{O}_3$ ,  $\text{FeO}$  and  $\text{K}_2\text{O}$ . Semiquantitative spectrographic analyses of major elements in samples from several of the districts are presented in Table 6. These analyses indicate decrease in Fe and Ti in the phyllic zone of the Margaret deposit, and decreases in Mg, Ca, Na, and increases in K and Fe in the Washougal district. The changes in whole rock chemistry resulting from phyllic/argillic alteration are commonly variable as a consequence of differing original rock chemistry, variations in alteration intensity, and conflicting mineralogic effects caused by superimposed hypogene and supergene processes.

Tourmaline-quartz alteration is usually associated with breccia pipes in the Washougal, North Santiam, and Bohemia districts. The diagnostic minerals of this assemblage are present in variable amounts, and they may be accompanied by sericite, potassium feldspar, magnetite, hematite, actinolite, sphene, and (or) apatite. Most breccia pipes contain minor amounts of sulfide minerals which may

Table 6. E-spec data for major elements (in %), rock types, and alteration types.  
More accurate major-oxide analyses are available in Appendices 3 or 5 for  
samples noted with an asterisk (\*).

Rock type	Glacier Peak						Margaret				Washougal			North Santiam		Blue River		Bohemia		Lower Detection Limit
	GP-2*	GP-3*	GP-4*	GP-5	GP-8	GP-15	MM-1*	MM-2*	MM-3*	MM-4*	WA-11*052A	WA-224A		NS-11*	NS-1-2052	BR-4*	NR-1*	BD-1*	BD-4*	
	QM	QD	Monz	QD	GD	Monz	GD	GD	GD	GD	GD	GD-BX	GD-BX	GD	GD	GD	Gran	QM	GD	
Altn type	prop	pot?	phy	unalt	unalt	pot	prop	phy	pot	phy	prop	phy	pot	prop	pot	prop	prop	prop	prop	
Si	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	1 Si
Ti	.07	.3	.01	.3	.2	.3	.5	.3	.5	.5	.5	.5	.3	.5	.3	.2	.2	.5	.3	.001 Ti
Al	7	7	5	10	7	7	7	7	7	7	7	7	3	10	7	7	7	7	5	0.5 Al
Fe	.5	2	.5	3	2	3	3	1.5	1.5	1.5	2	3	3	3	2	1.5	.7	2	1.5	0.05 Fe
Mg	.1	.7	.02	1.5	1	1	.5	.5	.5	1	.7	.2	.3	1	1	1	.2	.7	.3	0.02 Mg
Ca	.5	3	.1	5	3	2	2	2	3	3	3	.1	1.5	3	3	3	1	3	3	0.05 Ca
Na	2	2	.3	3	2	2	2	2	3	2	3	N	2	5	2	3	3	3	2	0.2 Na
K	5	2	5	3	1	3	1	1	2	1	1	3	1	3	1	2	2	2	.5	0.5 K

include pyrite, chalcopyrite, bornite, molybdenite, and (or) pyrrhotite.

Limited surficial exposures of potassic alteration are found in the Bohemia, North Santiam, and Washougal districts (see Figs. 18, 20 and 27). The potassic assemblage in these districts includes biotite, potassium feldspar, tourmaline, quartz, and sericite. Abundant magnetite and pyrite with minor carbonate and epidote are present in potassically altered granodiorite in the Bohemia district. In the North Santiam district, potassium feldspar is relatively uncommon and kaolinite is part of the assemblage. Hematite, magnetite, and epidote are associated with potassic alteration in the Washougal district. The potassic assemblage in the Glacier Peak deposit includes sericite, quartz, chlorite, and carbonate in addition to the characteristic biotite and potassium feldspar. A similar assemblage is present in the potassic zone of the Margaret deposit, although the potassium feldspar and biotite are present only in small amounts. Retrograde alteration has resulted in the partial replacement of wispy hydrothermal biotite by chlorite.

Potassic alteration typically results in the addition of K and removal of Ca and Na (Titley and Beane, 1981 and references cited therein). In the North Santiam district, these chemical changes include increases in the concentrations of  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  and decreases in those of  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{FeO}_t$ , and  $\text{CaO}$  (Olson, 1978). An increase in the concentration of K and decreases in those of Ca and Na accompanied potassic alteration at the Glacier Peak deposit (Rose,

1964). Spectrographic data (Table 6) also indicate increases in K in the potassic zone of the Margaret deposit, and the removal of Ca and Na from samples of this zone in the Washougal district.

The types and areal distribution of hydrothermal alteration in the Western Cascades are generally similar to those of mineralized areas and porphyry-type mineralization elsewhere in the circum-Pacific region. The extensive areas of propylitized rock containing smaller localized zones of argillic/phyllic alteration and tourmalinized breccia pipes are suggestive of porphyry-type mineralization. However, the presence of small areas of potassic alteration in the Bohemia district, and the direct association of potassic alteration with porphyry-type mineralization in the North Santiam and Washougal districts, constitute compelling evidence that the Western Cascades has gone unrecognized as a potentially important porphyry copper province.

#### Trace Element Geochemistry

The concentrations of trace metals (copper, molybdenum, lead, zinc, and silver) were determined for 375 samples from the Western Cascades. Samples of volcanic and plutonic rock, both altered and unaltered, and mineralized and unmineralized were evaluated. Statistical highlights of these data for samples from districts of the Western Cascades, and for smaller suites of the Glacier Peak and Margaret porphyry-type deposits of Washington, are summarized in Tables 7-11. Although both the median and mean (X) values provide a

Table 7. Summary of copper concentrations (in ppm) based on analyses of N samples from the Glacier Peak (GP) and Margaret (MM) porphyry deposits and the Washougal (WA), North Santiam (NS), Detroit Dam (DD), Quartzville (QV), Blue River (BR), Bohemia (BO), and South Umpqua (SU) districts.

District	Min	Max	Med	$\bar{X}$	N	$\bar{X}'$	N'
GP	90	16,200	3705	4791	14		
MM	380	11,400	2150	3683	8		
WA	12	164,000	100	5966	56	142	48
NS	10	84,000	55	3199	58	98	49
DD	6	2300	40	124	33	56	32
QV	5	1700	20	58	84	55	57
BR	8	160	25	33	37	33	37
BO	<5	22,300	25	452	59	48	57
SU	12	115	35	36	48	36	48
All w/o GP & MM				1488	375	68	328

Table 8. Summary of molybdenum concentrations

District	Min	Max	Med	X	N	$\bar{X}$	N'
GP	1	690	5.5	78	14		
MM	4	780	11	112	8		
WA	< 1	6500	2.0	130	56	2.3	50
NS	< 1	455	< 1	10.4	58	1.6	54
DD	< 1	17	1.0	2.0	33	1.6	32
QV	< 1	49	< 1	2.5	79	1.0	74
BR	< 1	5.0	< 1	.9	37	.9	37
BO	< 1	72	< 1	3.6	58	.9	55
SU	< 1	19	3	3.7	48	3.1	46
All w/o GP & MM				23.2	369	1.9	348

Table 9. Summary of lead concentrations

District	Min	Max	Med	$\bar{X}$	N	$\bar{X}'$	N'
GP	7	100	18	35	14		
MM	8	12	8.5	9	8		
WA	4	100	11	17	56	16	55
NS	6	205	30	36	58	29	55
DD	4	550	11	28	33	12	32
QV	5	1040	10	63	84	15	76
BR	4	140	10	13	37	10	36
BO	3	90,000	19	2257	59	18	52
SU	5	2100	25	92	48	26	44
All w/o GP & MM				392	375	18	350

Table 10. Summary of zinc concentrations

District	Min	Max	Med	$\bar{X}$	N	$\bar{X}'$	N'
GP	15	820	167	211	14		
MM	13	100	33	38	8		
WA	5	955	35	70	56	46	54
NS	20	1740	70	143	58	76	49
DD	8	160	30	42	33	38	32
QV	10	1200	55	97	84	57	75
BR	10	480	50	64	37	49	35
BO	25	72,000	80	2401	58	70	45
SU	10	3660	65	208	48	66	42
All w/o GP & MM				462	375	58	332

Table 11. Summary of silver concentrations

District	Min	Max	Med	$\bar{X}$	N	$\bar{X}'$	N'
GP	< 0.3	13.8	3.7	4.3	14		
MM	0.4	1.1	0.6	0.7	8		
WA	0.1	31.1	0.4	1.2	56	0.4	51
NS	0.3	50.9	0.6	2.5	58	0.6	54
DD	< 0.2	2.3	0.4	0.5	33	0.4	32
QV	0.2	10.0	0.5	0.8	84	0.6	81
BR	< 0.3	39.7	0.7	1.7	37	0.6	35
BO	< 0.3	22.9	0.7	5.5	59	0.6	54
SU	0.3	2.5	0.7	0.8	48	0.7	45
All w/o GP & MM				1.9	375	0.6	352

measure of the central, or "average", concentration of a metal in the rock samples from each district, comparisons of the two show that the mean value is almost always larger than the median. This apparent discrepancy is the result of "distortions" caused by a few highly anomalous metal-bearing samples. Accordingly, a modified mean ( $\bar{X}'$ ) also listed in Tables 7-11 was calculated by excluding samples which were grossly anomalous ( $> 1000$  ppm Cu,  $> 10$  ppm Mo,  $\geq 100$  ppm Pb,  $> 150$  ppm Zn, and  $> 1.5$  ppm Ag) to lessen the effect of a few samples on the mean. The number of samples excluded is simply  $N-N'$ . Thus,  $\bar{X}'$  represents a less distorted "average" value for each metal and may be interpreted as a central background value. Levinson (1974) has defined background as the normal range of concentrations for an element, or elements, in the rocks (soils, waters, etc.) of an area (excluding mineralized samples). For some metals,  $\bar{X}'$  may approach the upper limit of normal background, or a threshold value. For comparison, Field and others (1974) estimated threshold values for igneous rocks of the Pacific Northwest at 50 ppm Cu, 1 ppm Mo, 30 ppm Pb, 100 ppm Zn, and 1 ppm Ag. Concentrations greater than these threshold values indicate the possible presence of metallization.

The concentration of some metals varies from one district to another, and this interdistrict variation is documented by differences in the maximum, median, and modified mean values. For example, the Glacier Peak deposit contains relatively high concentrations of Cu, Mo, and Zn (the Zn, however, is not present in economic quantities) whereas the Margaret deposit is characterized by

high Cu and Mo values. In the Western Cascades, Cu is found in larger amounts in the Washougal and North Santiam districts, whereas values for Mo are higher in the Washougal and South Umpqua districts. The North Santiam and South Umpqua districts contain higher Pb concentrations. Moreover, Zn is more abundant in these two districts and in the Bohemia district as well. Concentrations of Ag are essentially identical in all districts. Thus, the Washougal district is higher in Cu and Mo, the North Santiam in Cu, Pb, and Zn, and the South Umpqua in Mo, Pb, and Zn.

Ternary plots of the relative proportions of Cu, Pb, and Zn provide another means of comparing metal concentrations in these districts. Distributions of these data are given in Figures 28, 29, and 30, and they illustrate two principal metallogenic sample populations. The Glacier Peak and Margaret deposits and the Washougal and North Santiam districts all contain numerous samples in which Cu predominates over the other metals. A broad cluster of points with subequal amounts of Cu and Zn and lesser amounts of Pb are found in all districts except the Washougal and the Glacier Peak and Margaret deposits. The Margaret and Glacier Peak samples were all taken from near the center of porphyry-type mineralization, which clearly dictates the excess of samples dominated by Cu. Samples from the Washougal district, however, were obtained over a much larger area and are not restricted to porphyry-type mineralization, yet the distribution of points indicates that metallization throughout this district is largely dominated by Cu.

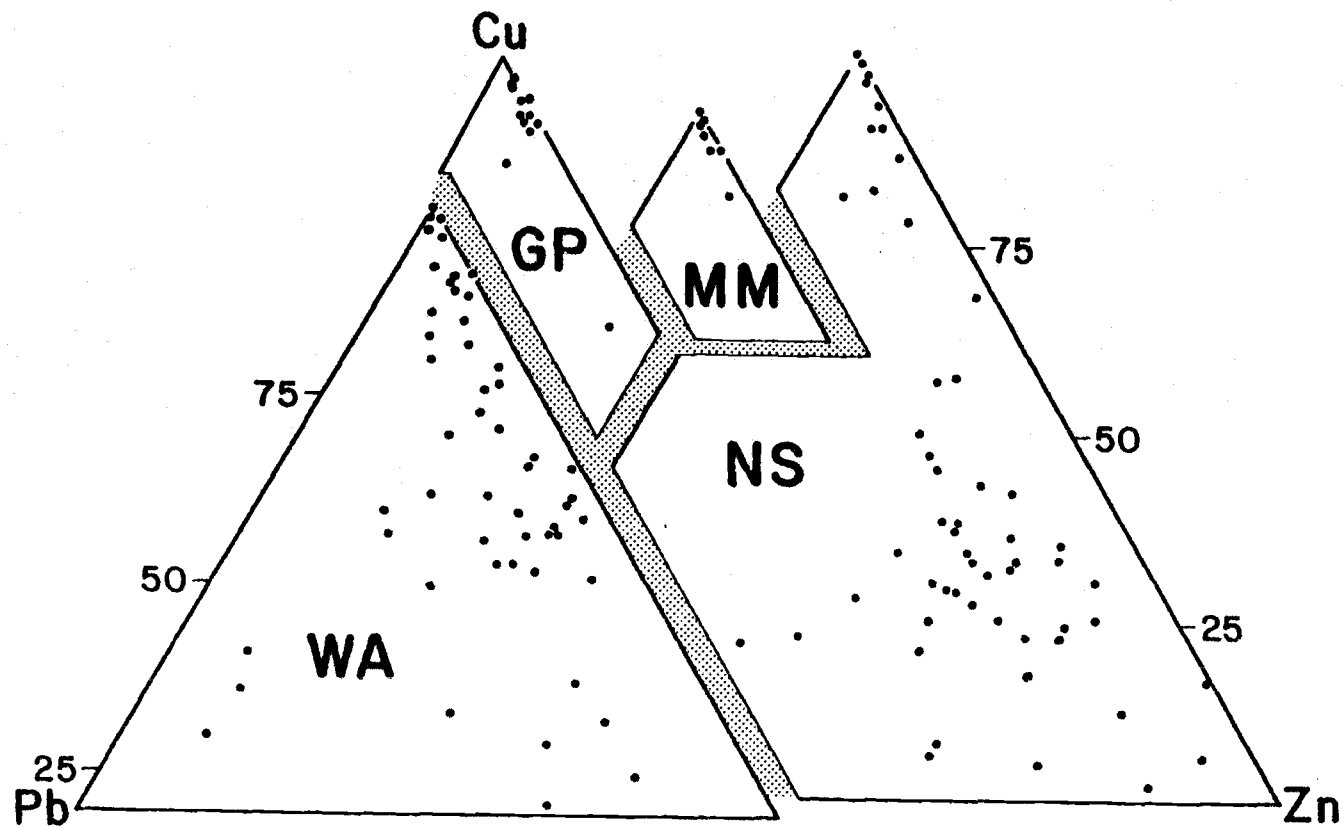


Figure 28. Ternary Cu-Pb-Zn diagrams for samples from the Washougal (WA), Glacier Peak (GP), Margaret (MM) and North Santiam (NS) districts.

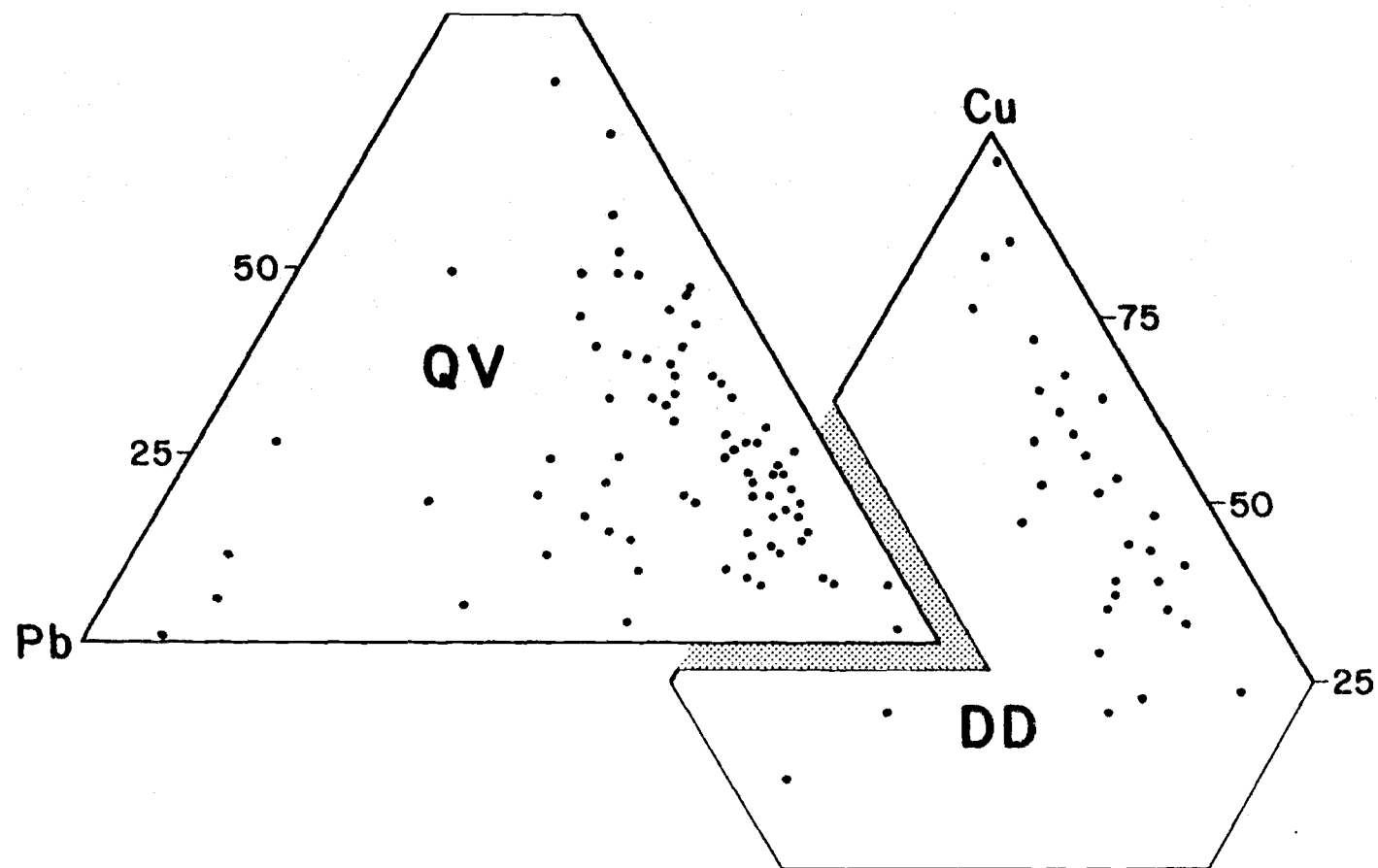


Figure 29. Ternary Cu-Pb-Zn diagrams for samples from the Quartzville (QV) and Detroit Dam (DD) areas.

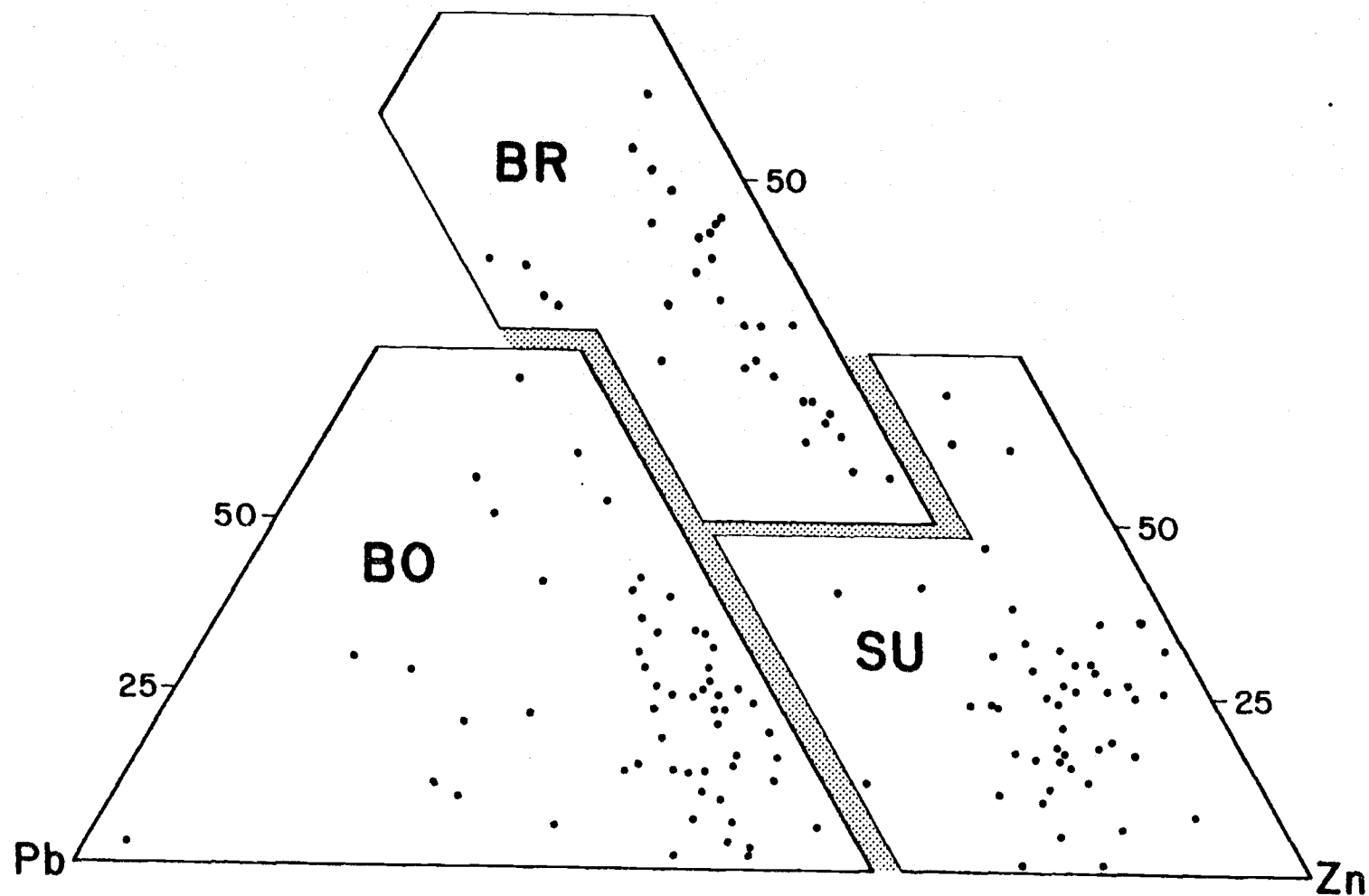


Figure 30. Ternary Cu-Pb-Zn diagrams for samples from the Bohemia (BO), Blue River (BR), and South Umpqua (SU) districts.

Correlation coefficients as shown in Table 12 were calculated to determine possible relationships between the different metals. The rank correlation coefficient,  $r_s$ , was used to test the hypothesis of independence between any two metals within each district and for the entire suite of samples (excluding Glacier Peak and Margaret deposits). Correlation coefficients with absolute values below the test statistic for the 97.5 percent confidence level are not statistically significant and have been omitted from Table 12. There are weak, but statistically significant correlations between Cu and Mo, and between Pb and Zn for the entire population of samples. However, there is a weak positive correlation between Cu and Zn for samples of the Quartzville, Washougal, Detroit Dam, and the South Umpqua districts. Because correlations between metals are weak within the individual districts, the somewhat better correlations obtained for the entire sample suite may be simply an artifact of the large sample size.

Semiquantitative spectrographic analyses for 35 elements were performed on 18 samples by Specomp Services of Boise, Idaho. The results, and the lower detection limit for each element are listed in Table 13. Eight major elements (Si, Ti, Al, Fe, Mg, Ca, Na, and K) were presented in Table 6. Elements that were undetected by these analyses include Bi (10 ppm detection limit), Cd (20 ppm), and Nb (10 ppm).

Concentrations of the trace elements in these samples have been evaluated with respect to location, rock type, and alteration type.

Table 12. Rank-correlation coefficients between pairs of metals

<u>Sample Group</u>	<u>Cu/Mo</u>	<u>Pb/Zn</u>	<u>Cu/Zn</u>	<u>Pb/Ag</u>	<u>Test Value</u>
All samples	.202		.201		.106
All samples w/o Quartzville	.259	.489		.208	.121
Plutons only	.316				.168
Plutons without Quartzville		.421			.193
Washougal			.353		.274
Detroit Dam			.419		.355
Quartzville			.575		.220
South Umpqua			.367		.304

Table 13. E-spec data, rock types, and alteration types. P reported in %, all other elements reported in ppm. N: not detected, L: below limit of determination.

Rock:	Glacier Peak						Margaret				Washougal		N. Santiam		Blue River			Bohemia		Lower Detection Limit	
	GP-2 QM	GP-3 QD	GP-4 Monz	GP-5 QD	GP-8 GD	GP-15 Monz	MM-1 GD	MM-2 GD	MM-3 GD	MM-4 GD	WA-11 GD	WA- 058A GD-BX	WA- 224A GD-BX	NS-11 GD	NS-1- 2052 GD-BX	BR-4 GD	NR-1 GRAN	BO-1 QMp	BO-4 GD		
Alt'n	prop	pot ?	phy	unalt	unalt	pot	prop	phy	pot	phy	prop	phy	pot	prop	pot	prop	prop	prop	prop		
Ag	1	20	7	1	.5	30	L	2	1	L	N	2	2	N	15	N	N	N	N	0.5	Ag
As	N	200	2000	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	200	As
Au	N	N	N	30	N	N	N	N	N	N	N	N	N	N	15	N	N	N	N	10	Au
B	N	50	50	30	30	30	30	50	20	30	30	200	20	20	10	10	50	20	10	10	B
Ba	700	200	1000	1000	500	1,000	30	200	100	50	500	700	150	700	150	500	700	700	100	10	Ba
Be	2	5	N	3	2	2	5	5	5	5	5	5	3	5	3	3	5	5	5	1	Be
Co	N	10	N	15	10	10	20	N	10	10	N	15	30	20	20	20	N	10	N	10	Co
Cr	300	70	200	100	100	50	100	100	100	70	50	30	30	100	30	70	100	150	70	20	Cr
Cu	1000	10,000	3000	1000	150	10,000	1000	15,000	7000	1500	70	7000	20,000	100	5000	200	150	100	200	5	Cu
La	N	N	N	20	N	N	N	20	N	N	N	N	N	20	N	N	50	20	N	20	La
Mn	150	2,000	300	1500	1500	700	100	150	150	200	1000	200	200	3000	700	700	200	1000	200	10	Mn
Mo	N	5	50	7	5	10	5	20	1000	N	N	5	5	5	5	N	N	5	30	5	Mo
Ni	5	5	5	10	5	30	10	10	20	20	10	20	70	20	20	20	5	5	5	5	Ni
P	N	0.1	N	N	0.1	N	0.1	0.1	0.1	0.1	0.1	N	N	0.1	0.2	0.1	N	0.1	0.1	0.1	P
Pb	50	100	20	15	15	200	10	10	10	10	N	150	15	30	50	10	10	30	15	10	Pb
Sb	N	N	1000	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	100	Sb
Sc	N	15	N	30	10	10	5	5	10	15	5	7	N	15	10	10	N	10	10	5	Sc
Sn	N	10	N	N	N	10	N	10	15	N	N	10	10	N	10	N	N	N	N	10	Sn
Sr	200	500	N	700	500	300	300	500	500	500	500	N	300	700	500	500	300	500	500	100	Sr
V	10	200	10	300	300	200	100	150	150	200	150	150	20	150	150	100	30	150	100	10	V
W	N	200	N	N	N	50	N	N	N	N	N	N	N	N	N	N	N	N	N	50	W
Y	N	10	10	20	10	20	10	10	N	N	10	10	N	30	15	10	20	30	20	10	Y
Zn	N	1000	L	L	N	200	N	N	N	N	N	N	N	L	L	N	N	L	N	200	Zn
Zr	50	30	30	70	70	30	70	30	70	50	50	100	50	150	70	70	50	100	100	10	Zr

Samples from the Glacier Peak deposit are unique because of their higher concentrations of Ag, Zn, Ba, and V. In addition, As, Sb, and W were detected only in samples from this deposit. These differences may be a consequence of the greater age and composition of the continental granitic crust which underlies much of northern Washington. That is, some of these metals may have been "inherited" from a deeper crustal source region or from the surrounding host rocks (Titley and Beane, 1981 and references cited therein).

Evaluation of samples by rock type reveals few unexpected trends. The most felsic rocks contain low concentrations of Ni (5 ppm) and intermediate concentrations of Ba (700 ppm). The most mafic rocks, monzonites and quartzdiorites, have high concentrations of Ba (1000 ppm). Granodiorites of intermediate composition exhibit the highest contents of Co (up to 30 ppm). Other primary differences in the chemistry of these rock types are probably obscured by variations superimposed by subsequent hydrothermal alteration. During such events, some elements may be leached from the rocks as other elements are added. In samples from the Western Cascades and Glacier Peak and Margaret deposits, potassic and phyllic alteration may have added Ni, Ag, Cu, Mo, Sn, and Pb and may have leached Mn, Zr, and Y. In addition, rocks subjected to potassic alteration contain higher concentrations of W (detected only in the two samples from Glacier Peak) and lower concentrations of Cr (56 ppm average) compared to other alteration assemblages (110 ppm average). Sb was detected only in a sample from the phyllic zone of the Glacier Peak deposit.

## Sulfur Isotope Geochemistry

Sulfur isotope analyses were determined for sulfide minerals from the Western Cascades, Margaret, and Glacier Peak deposits to evaluate variations in  $\delta^{34}\text{S}$  with respect to variations in latitude and level of erosional exposure; to determine the source of sulfur in these deposits; and to calculate the temperatures of sulfide deposition. Such applications are possible because of the studies of the chemical and temperature controls of sulfur isotope fractionation (Field, 1966a, 1966b; Jensen, 1967; Sakai, 1968; Bachinski, 1969; Field and Moore, 1971; Field and others, 1971; Lange and Cheney, 1971; and Ohmoto, 1972). Comparisons of the isotopic temperature estimates to those obtained from fluid inclusions provide potentially useful information concerning the depth of sulfide deposition because the two methods are independent of each other and the former does not require a correction for pressure. The isotopic temperature estimates are based on experimental equilibrations by Kajiwara and Krouse (1971), Czamanske and Rye (1974), and other investigators whose results have been integrated and summarized by Ohmoto and Rye (1979).

### Experimental Methods

Sulfides were selected, preferably from samples with coexisting sulfide pairs, and were hand picked from coarsely crushed rock. Most samples were estimated to be 95 percent pure.  $\delta^{34}\text{S}$  values of each mineral are presented in Table 14. A histogram of  $\delta^{34}\text{S}$  values is presented in Figure 31.

Table 14. Sulfur isotope data.

Abbreviations: Vn = vein; Ds = disseminated; Bx = breccia; and Vn1 = veinlet. All analysis were performed by Global Geochemistry except those noted by \*U.S. Geological Survey and \*\*Nagoya University.

District	Sample	Type	Mineral	$^{34}\text{S}$ %
Glacier Peak	214-57	Ds	Py	2.9
			Cp	2.4
	GP-1	Ds	Py*	2.6
			Cp*	3.9
Mount Margaret	71-64	Ds	Py	2.3
			Cp	0.9
Washougal	MQ-1	Bx	Py*	0.1 <sup>1</sup>
			Cp*	0.5 <sup>6</sup>
	16-696	Bx	Py	4.1
			Cp	3.9
	SS-4	Ds/Bx	Py*	4.7
			Cp*	2.9
North Santiam	DDH 3-500	Vn1	Cp*	4.2
			Bn*	5.0
	DDH 3-500	Bx	Cp	1.1
			Bn	4.2

District	Sample	Type	Mineral	$^{34}\text{S}$ %
	DDH 2-796	Bx	Cp*	4.6
			Bn*	4.0
	DDH 17-1600		Cp*	4.9
	NS-V-1	Vn	Py	-0.4
			S1	-2.1
	NS-V-4	Vn	Py*	2.9
			S1*	2.6
	NS-V-S-2	Vn	S1	1.0
			Gn	-0.5
Quartzville				
	QV-V-1	Vn	S1*	1.2
			Gn*	-1.7
	QV-V-2	Vn	S1**	2.1
			Cp**	1.9
			Gn**	-1.1
	QV-V-3	Vn	Py	1.1
			S1	1.9
			Cp	0.8
	QV-V-4	Vn	Py	0.8
			S1	0.4
			Gn	-0.3
	QV-V-6	Vn	Py*	1.0
			S1	1.9
			Cp	0.7
			Gn	-0.2

District	Sample	Type	Mineral	$^{34}\text{S} \%$
Blue River				
	BR-V-1	Vn	Py*	1.9
			S1*	0.8
			Cp*	1.7
			Gn	-0.8
Bohemia				
	B0 4	Bx	Py*	2.6
	B0-V-1	Vn	S1	2.2
			Cp	3.0
			Gn	1.0
	B0-V-2	Vn	S1	0.8
			Cp	0.6
			Gn	1.1
	B0-V-3	Vn	S1*	-2.3
			Gn*	-5.1
	B0-V-5	Vn	Py*	3.1
			S1	2.3
			Cp*	2.1
			Gn	0.1
	B0-V-8	Vn	Py**	3.5
			S1**	3.1
			Cp**	2.3
			Gn**	1.1

District	Sample	Type	Mineral	$^{34}\text{S}$ %
	B0-V-9	Vn	S1	3.1
			Gn	0.6
South Umpqua				
	SU-18	Ds	Py	4.0
	SU-23	Ds	Py	0.9
	SU-44	Vn	Py	2.6
			S1	2.8
			Gn	1.3

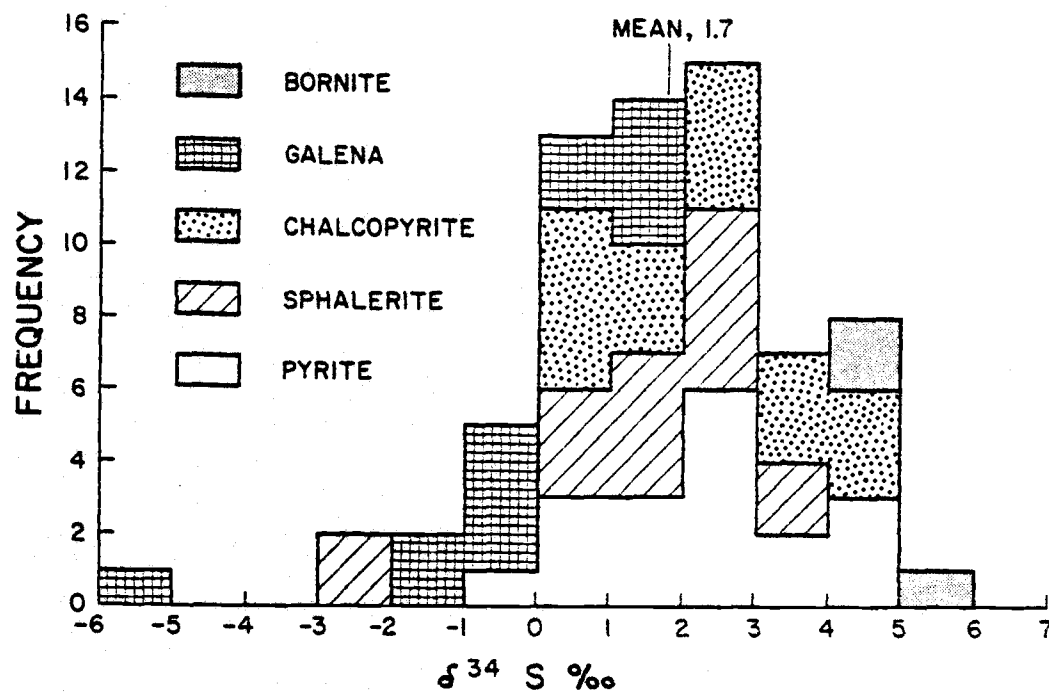


Figure 31. Histogram of  $\delta^{34}\text{S}$  values.

Sulfur was analyzed as  $\text{SO}_2$ . Analyses were made at the following labs: Global Geochemistry, Canoga Park, CA., (P.J. Mankiewicz); U.S. Geological Survey, Denver (C.W. Field, R.H. Fifarek, and J.F. Whelan); and the Department of Earth Sciences, Nagoya University, Japan (Y. Kiyosu).

Sulfur isotope data are reported as  $\delta^{34}\text{S}$  values in parts per thousand (permil, or ‰) between the sample (A) and the standard (std) as given by the equation:

$$\delta^{34}\text{S}\text{‰} = \frac{(^{34}\text{S}/^{32}\text{S})_{\text{A}} - (^{34}\text{S}/^{32}\text{S})_{\text{std}}}{(^{34}\text{S}/^{32}\text{S})_{\text{std}}} \times 1000$$

Positive or negative values reflect  $\delta^{34}\text{S}$  enrichment or depletion of the sample relative to the standard, which is the troilite phase of the Canon Diablo meteorite (Thode and others, 1961).

Experimental isotopic fractionation data from which temperatures were calculated have been referenced, revised, and summarized by Ohmoto and Rye (1979). Temperatures for the sulfide triplet of pyrite, sphalerite, and galena were calculated with the sulfur isotope thermometer of Smith and others (1977).

#### Variation of $\delta^{34}\text{S}$

Sulfides from the Cascades have a total range of -5.1 to +5.0 permil with a mean value of 1.7 permil. The range, mean, and standard deviation of  $\delta^{34}\text{S}$ , and the number of samples of pyrite, sphalerite, chalcopryrite, galena and bornite are presented in Table 15.

Table 15. Statistical parameters for  $\delta^{34}\text{S}$  values from the Cascades.

MINERAL	RANGE	MEAN	Std. Dev.	N
Pyrite	-0.4 to 4.7	2.3	1.4	18
Sphalerite	-2.3 to 2.6	1.4	1.6	16
Chalcopyrite	0.6 to 4.9	2.4	1.5	18
Galena	-5.1 to 1.3	-0.3	1.7	13
Bornite	4.2 to 5.0	4.4	0.5	3
Total	-5.1 to 5.0	1.7	1.8	68
Breccia and Disseminated Sulfides				
Pyrite	0.1 to 4.7	2.7	1.5	9
Chalcopyrite	0.6 to 4.9	2.9	1.6	10
Vein Sulfides				
Pyrite	-0.4 to 3.5	1.8	1.3	9
Chalcopyrite	0.6 to 3.0	1.6	0.9	8

$\delta^{34}\text{S}$  values plotted by district from north to south are displayed in Figures 32 and 33. It is obvious from this diagram that the variation of  $\delta^{34}\text{S}$  values of sulfides within one district is as great as that of the entire sample population. However, on closer examination, it may be noted that the pyrite and chalcopyrite samples from breccia pipes and disseminated occurrences (Figure 32) tend to be somewhat enriched in  $\delta^{34}\text{S}$  relative to those from veins (Figure 33). The mean values of pyrite and chalcopyrite from the breccia pipes and disseminated samples are 2.7 and 2.9 permil, respectively. Average  $\delta^{34}\text{S}$  values for the same minerals from vein samples are 1.8 and 1.6 permil. However, when subjected to simple statistical tests to determine if the means of the vein and disseminated populations are identical, the hypothesis of equality cannot be rejected for either chalcopyrite or pyrite at the 95-percent confidence level.

$\delta^{34}\text{S}$  values for individual minerals were also plotted on maps of each district. However, the paragenesis of each district is too complex to reveal any spatial or temporal trends with such small sample suites.

The range of  $\delta^{34}\text{S}$  values of sulfides from the Cascades is similar to that of many other porphyry districts of the cordillera including Butte, Montana, and Morococha and Toquepala Peru (Field and others, 1983). The near 0 permil values probably indicate a magmatic source for the sulfur, unless other sulfur species have been removed from these systems. Sillitoe (1972) and many others have theorized that metals and magmas of the cordillera may have been derived

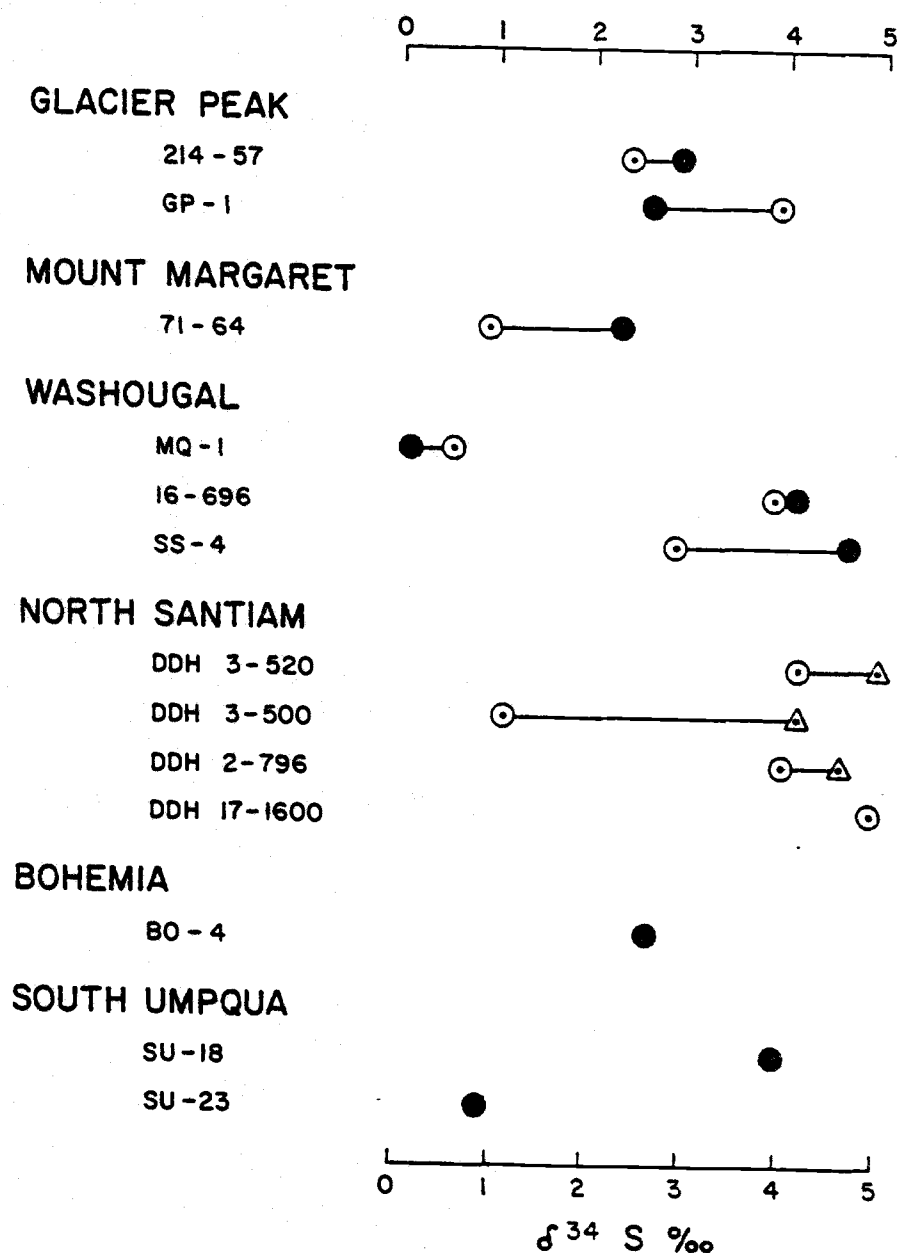


Figure 32. Range of  $\delta^{34}\text{S}$  of disseminated and breccia sulfides from the Cascades, plotted from north to south (closed circles, pyrite; open circles, chalcopyrite; open triangles, bornite; closed squares, galena; open squares, sphalerite).

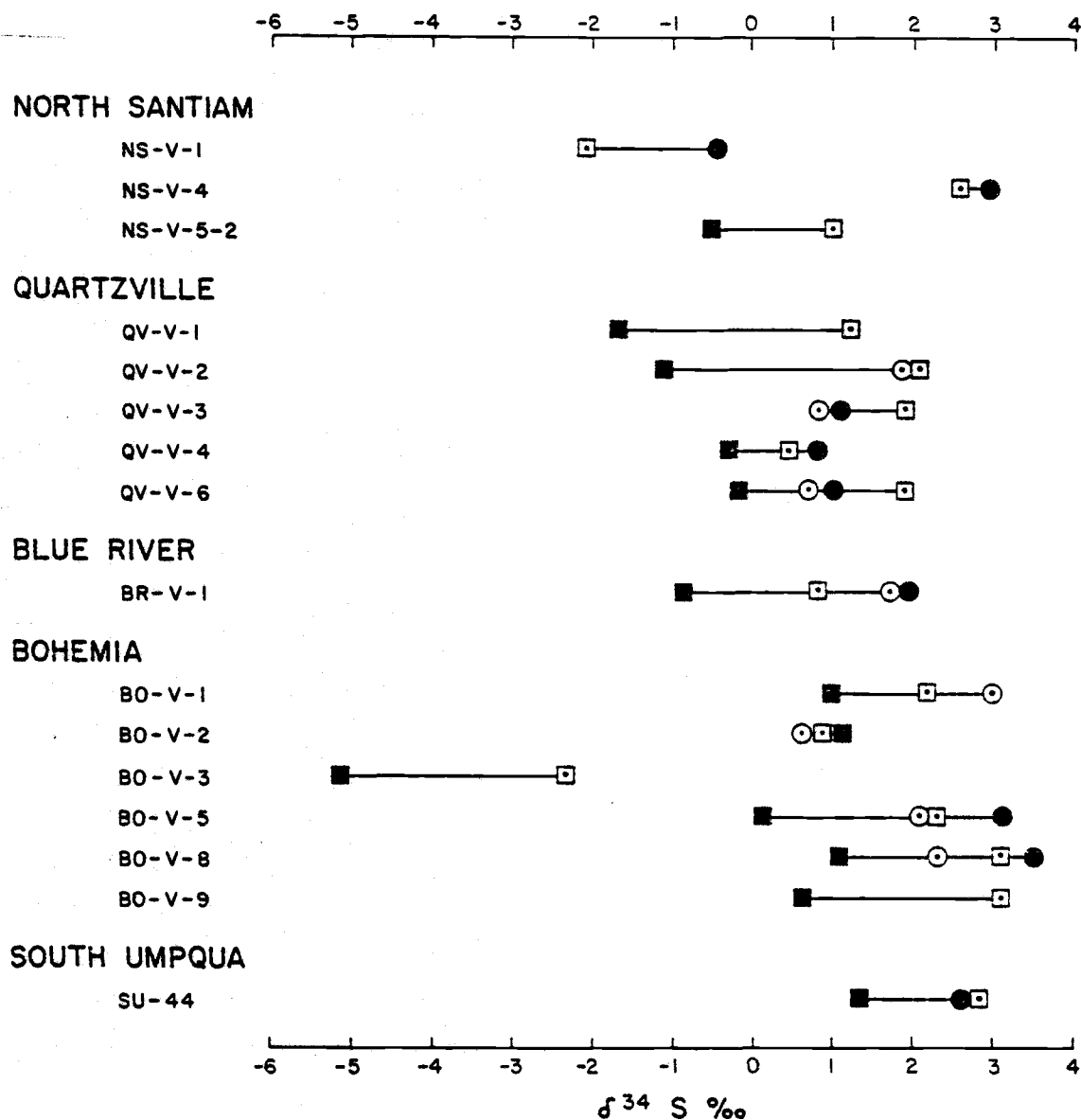


Figure 33. Range of  $\delta^{34}\text{S}$  of vein sulfides from the Cascades, plotted from north to south.

through subduction and anatexis of metal-bearing oceanic crust. Sulfur isotopes could serve as a potential tracer because of metalliferous marine sediments having high  $\delta^{34}\text{S}$  values (20 %) compared to typical magmatic values. However, such speculations are not supported by sulfur isotope data from the Cascades.

### Thermometry

Theoretical considerations (Sakai, 1968; Bachinski, 1969) and isotopic data from other ore deposits indicate that  $\delta^{34}\text{S}$  enrichment should decrease in the following order: pyrite, sphalerite, chalcopyrite, and galena. The mineral assemblages in some veins (Table 14) do not have this predicted order and were not formed under equilibrium conditions. If paragenetic observations and  $\delta^{34}\text{S}$  values indicated that the associated minerals of such an assemblage were co-precipitates, temperatures were calculated for that pair only. Although the enrichment trends are in the correct order, unreasonable temperatures were obtained for other samples as well. Many of these samples have complex paragenetic histories, and it is probable that the mineral pairs were not deposited under equilibrium conditions. In addition, equilibrium between mineral pairs is unlikely at the low temperatures (200°C) probable during the formation of many of these veins.

Temperatures were calculated from 36 mineral pairs and 3 sulfide triplets from 16 veins (Table 16). They indicate that vein-type mineralization occurred over a range from 45 to 740°C. Within one

Table 16.  $\Delta^{34}\text{S}$  ‰ values and isotopic temperatures.

District/Sample	Type	$\Delta^{34}\text{S} \%$						Tri-sulfide Thermo- meter p-s-g	T°C
		py-sl	py-cp	py-gn	sl-cp	sl-gn	Cp-gn		
Glacier Peak									
214-57	Ds		0.5 (675)						675
Mount Margaret									
71-64	Ds		1.4 (295)						295
Washougal									
MQ-1	Bx		0.5 (675)						675
16-696	Bx		0.2 (1225)						1225
SS-4	Ds/Bx		1.8 (226)						226
North Santiam									
NS-V-1	Vn	1.7 (150)							150
NS-V-4	Vn	0.3 (730)							?
NS-V-5	Vn					1.5 (420)			420
Quartzville									
QV-V-1	Vn					2.9 (225)			225
QV-V-2	Vn				0.2 (510)	3.2 (200)	3.0 (165)		200
QV-V-3	Vn	NE	NE		1.1 (60)				?
QV-V-4	Vn	0.4 (595)		1.1 (690)		0.7 (740)			?
QV-V-6	Vn				1.2 (45)	2.1 (315)	0.9 (530)		315
Blue River									
BR-V-1	Vn	1.1 (250)	NE	2.7 (340)	NE	1.6 (400)	NE	375	375
Bohemia									
BO-V-1	Vn				NE	1.2 (500)	2.0 (265)		265
BO-V-2	Vn				0.2 (510)	NE	NE		510
BO-V-3	Vn					2.8 (235)			235
BO-V-5	Vn	0.8 (340)	1.0 (395)	3.0 (310)	0.2 (510)	2.2 (300)	2.0 (265)	350	350
BO-V-8	Vn	0.4 (595)	1.2 (340)	2.4 (380)	0.8 (120)	2.0 (330)	1.2 (420)	425	380
BO-V-9	Vn					2.5 (265)			265
South Umpqua									
SU-44	Vn	NE		1.3 (610)		1.5 (420)			420

NE: not equilibrium assemblage

vein, temperatures calculated from three different mineral pairs range from 45 to 530°C, probably indicating a disequilibrium assemblage. Sphalerite-galena mineral pairs usually give the most realistic temperatures (200 to 500°C) for veins in which  $\delta^{34}\text{S}$  values were available for more than one mineral pair. A comparison of isotopic and fluid inclusion temperatures (Table 17) reveals that isotopic estimates are generally higher and more variable than those from fluid inclusions, in part, because homogenization temperatures commonly require a pressure correction of up to +300°C to be discussed in the chapter that follows on fluid inclusions.

Chalcopyrite-pyrite pairs from porphyry-type mineralization at Glacier Peak and the Washougal district gave isotopic temperature estimates of 675°C. This temperature is comparable to filling temperatures of fluid inclusions at Bingham, El Salvador, and San Manuel (Nash, 1976) and to isotopic temperatures from the Panguna deposit (Eastoe, 1979). Other mineral pairs from porphyry-type and breccia mineralization give unrealistic temperature estimates (226, 295, and 1225°C), probably because the minerals were not paragenetic equivalents.

In summary, temperatures of vein-type mineralization probably ranged from 200 to 600°C, whereas at least some porphyry-type mineralization took place at about 675°C.

Table 17. Comparison of isotopic temperature estimates to homogenization temperatures of fluid inclusions.

Sample	$T_{34_S}^{\circ\text{C}}$	$T_h^{\circ\text{C}}$
NS-V-5-2		278-303
V-5-1	420 (sl-gn)	
B0-V-1	500 (sl-gn)	261-263
	265 (cp-gn)	
B0-V-8	595 (py-sl)	295
	340 (py-cp)	
	380 (py-gn)	
	120 (sl-cp)	
	330 (sl-gn)	
	420 (cp-gn)	
	425 (py-sl-gn)	
B0-V-9	265 (sl-gn)	268-310

## Fluid Inclusion Studies

### Methods

More than 80 doubly polished plates of quartz from veins, breccias, and altered plutons were examined with the petrographic microscope to determine the types and abundances of fluid inclusions contained therein. Selection of samples for microscope analysis on the freezing and heating stage depended on the size of the inclusions, their abundance, and the size of the host mineral. The maximum size of inclusions in samples from the Western Cascades is about 20 microns in diameter. However, most inclusions are much smaller, on the order of 4 microns or less. Superposition of inclusions results in poor optical clarity. Samples from breccia pipes and areas of potassic alteration often contain very small grains of quartz in a matrix of less transparent minerals such as cloudy feldspar, clays, and iron-titanium oxides. Plates from these samples had to be ground thinly to improve their optical clarity, but were then too fragile for use on the freezing and heating stage, although descriptive data were obtained for these samples. Thus, only 11 samples were useful for analysis on the heating and freezing stage.

Primary or pseudosecondary inclusions, as defined by Roedder (1967; 1979), were selected where possible, but not uncommonly, the secondary inclusions located along fracture planes were the only ones sufficiently large and abundant to be studied on the heating and freezing stage. Since many of the samples studied show evidence of

repeated pulses of mineralization, these secondary inclusions are undoubtedly of hydrothermal origin, as is also indicated by their filling temperatures. However, because of the reconnaissance nature of this study and the location and density of suitable samples it was not possible to accurately define the paragenetic relationship of the fluid inclusions in one sample to those in other samples, as may sometimes be accomplished in detailed studies of inclusions from a well-developed mine or district.

A Chaixmeca freezing and heating stage (Poty and others, 1976) was used to determine homogenization and freezing temperatures of inclusions. The stage was calibrated with several standards and replicate measurements of melting temperatures of the standards showed a reproducibility of  $\pm 5^{\circ}\text{C}$ . Errors in calibration can arise from many sources (Hollister and others, 1981). However, for a reconnaissance study such as this, the homogenization temperatures and salinity data provide estimates which enable general comparisons to similar deposits.

### Types of Inclusions

Three main types of inclusions were observed in material from the Western Cascades and these correspond to inclusion types I, II, and III of Nash (1976).

Type I inclusions are of moderate salinity and contain both liquid and vapor phases. One or more daughter minerals may be present including dawsonite (?), rhombohedral carbonate, anhydrite,

hematite, and possibly other unidentified phases. These inclusions from the Western Cascades vary in salinity from nearly 0 to 18 weight percent NaCl equivalent, compared to up to 23 weight percent in other porphyry districts (Nash, 1976). Type I inclusions are ubiquitous in intrusive rocks, wall rocks, and veins of porphyry districts. They are commonly secondary and formed during repeated episodes of fracturing and annealing. In the Western Cascades, and elsewhere, they are associated with propylitic and phyllic alteration and with ore veins. Type I inclusions make up the vast majority of inclusions found in samples from the Western Cascades.

Type II inclusions contain fluid plus more than 60 volume percent vapor, and they may also contain hematite as a daughter mineral. In porphyry deposits, the salinity of this type of inclusion usually ranges from 0.4 to 7 weight percent (Nash, 1976). Unfortunately, inclusions of this type from the Western Cascades were not suitable for study on the freezing stage. The abundance of type II inclusions varies widely. In most porphyry deposits, they are associated with quartz veins and igneous quartz of the porphyries. In the Western Cascades, they are found primarily in samples from breccia pipes. The association of type II inclusions with type I and III which homogenize at similar temperatures and are on the same plane of secondary inclusions suggests boiling of the hydrothermal system. Although boiling is documented by filling temperatures and inclusion paragenesis in only two samples from the Western Cascades, the association of type I, II, and III inclusions in other samples

suggests that boiling occurred in many breccia pipes and possibly elsewhere in the hydrothermal systems.

Type III inclusions contain halite as a daughter mineral, and are characteristic of porphyry copper deposits (Nash, 1976; Roedder, 1971), but are not exclusive to that environment. In addition to halite, these inclusions may contain sylvite, hematite, anhydrite, a rhombohedral carbonate, and other daughter minerals. The salinities of these inclusions range from 30 to 50 weight percent NaCl equivalent. Filling temperatures from the type III inclusions from the Western Cascades range from 246° to over 386°C, compared to a range of 225° to 725°C in other porphyry deposits (Nash, 1976). Type III inclusions are commonly observed in igneous quartz of the porphyries, and in many quartz sulfide veins. In the Western Cascades, this type of inclusion is most common in quartz from intrusive rocks and breccia pipes which have been altered to a potassic assemblage.

#### Daughter Minerals

A variety of solid phases were observed in many of the fluid inclusions and were found to be particularly abundant in type III inclusions. Some inclusions contain as many as six daughter minerals. Halite is the most common of these and is isotropic with a sharp cubic crystal form. Unfortunately, the reaction of halite with water to form the birefringent mineral  $\text{NaCl} \cdot \text{H}_2\text{O}$  upon freezing was not observed, because most samples which contained halite were not optically or physically suited for use on the freezing stage. Sylvite

sometimes accompanies halite, and is identified by its isotropism and rounded cubic form. Other daughter minerals tentatively identified include a rhombohedral carbonate (high birefringence and rhombohedral form), anhydrite (elongate rectangular prisms with moderate birefringence), dawsonite (bundle of fibers, see Coveney and Kelley, 1971), and hematite (translucent reddish brown flakes). In addition, some samples contain one or two very small opaque phases, perhaps sulfides, and possibly a third isotropic mineral.

#### Filling Temperatures

Filling temperatures were determined for 31 representative fluid inclusions contained in 11 polished plates (Table 18). Most of these inclusions are type I and III and homogenized in the liquid phase. The minute amount of liquid in type II vapor dominated inclusions was difficult to observe, but approximate filling temperatures were obtained for two samples.

Filling temperatures of inclusions from vein quartz range from 167° to 319°C. Of these temperatures, 71 percent are in the range from 237° to 294°C, and all of the samples contain some type I inclusions which also homogenize in this temperature range.

Quartz from breccia pipes contains inclusions which homogenize at temperatures of 240° to greater than 386°C. Only one of four samples contains inclusions which homogenize below 280°C. Thus, breccia pipes may not have been affected by the later (?) low temperature episodes of hydrothermal activity. Type III (halite

Table 18

## Temperature and salinity data from fluid inclusions

District	Sample Number	Description	Inclusion Type	Filling Temp.	Salinity Freezing Temp.	Wt. % NaCl	Comments
Glacier Peak	681-396	vein quartz	I-s	171-173	-10.5- -13.2	13- 16.5	
	101-792	quartz assoc. with phyllic alteration	I-s	162-184	-9.0- -12.2	12- 16	
Washougal	B-3	quartz in breccia pipe	II & III	386	-10?	13?	boiling?
	SS-696	quartz in breccia pipe	I & II	361-378	-15	18	boiling
North Santiam	V-4-2	vein quartz	I-s	237-294			
	V-5-1	vein quartz	I-s	278-303	-14	17.5	
	B-1Q	vein quartz in breccia pipe	I & II	287	-7.2	10.5	boiling
	CC-278	quartz in breccia pipe	III-s	246-283		30 (est)	
Bohemia	V-1	vein quartz	I-s	261-263	-9.5- -10	13 1	
	V-2	vein quartz	I-s	167-243	-11- -11.4	15.5	
	V-8	vein quartz	I-s	295	-6- -10	9- 15	analysis by R. A. Schmuck
	V-9	vein quartz	I-s	268-310	-0.6- -3.3	0-4	

bearing) inclusions from breccias homogenize over the full range of filling temperatures of samples from breccia pipes.

Quartz associated with coarse-grained carbonate and sericite at the Glacier Peak porphyry deposit contains type I inclusions which homogenize from 162° to 183°C, the lowest observed temperatures. These inclusions may have formed during a late stage of silica flooding which post-dated ore deposition (Grant, 1982).

#### Salinity Data

The freezing point depression of fluids was determined from 14 inclusions contained in ten samples. Because of the difficulty in observing the complete melting of ice in these small inclusions (see Roedder, 1963), the data should be considered approximations at best. The salinity of the type I inclusions in veins ranges from 17.5 to nearly 0 weight percent NaCl equivalent as deduced from freezing-melting point depressions that ranged from -14° to -0.6°C. In breccia pipes, salinities for type I inclusions range from 13 to 18 weight percent (-10° to -15°C), whereas the type III inclusions, which contain visible halite, have salinities greater than 30 weight percent NaCl. The salinities of inclusions from the Glacier Peak samples range from 12 to 16.5 weight percent NaCl equivalent (-9° to -13.2°C).

### Pressure and Depth Estimation

Filling temperatures represent minimum temperatures of fluid entrapment, and may require pressure corrections equivalent to +5 to +300°C depending on the depth (pressure) of formation. Estimates of the fluid pressure during mineralization are essential to the evaluation of fluid inclusion filling temperatures, especially when these data are used in detailed studies of paragenetic sequences within a deposit. Such independent estimates of pressure are generally made using geologic arguments concerning the depth of overburden during mineralization, or on the basis of the  $\text{CO}_2/\text{H}_2\text{O}$  mole ratio and the salinity of fluids in the inclusions themselves (see Landis and Rye, 1974). A lack of appropriate geologic and analytical data preclude an independent estimate of depth for most areas in the Western Cascades. Comparisons to data in the Bingham and Pasto Bueno hydrothermal deposits indicate that maximum pressure corrections would be less than 100° and probably less than 50°C (Roedder, 1971; 1972; Landis and Rye, 1974).

Fluid inclusions themselves may allow a very crude estimate of pressure and depth if there is evidence of boiling (Roedder, 1971). Coexisting gas-rich (type II) and moderate- or high-salinity (type I or III) inclusions which homogenize at the same temperature indicate that the fluid was trapped while boiling (i.e. on the liquid-vapor curve). Therefore, the homogenization temperatures of these inclusions need no pressure correction and may be used to estimate the

pressure at which these inclusions formed using data from the system NaCl-H<sub>2</sub>O (Sourirajan and Kennedy, 1962; Haas, 1971). Assuming hydrostatic conditions, application of such relations indicates pressures of approximately 154 bars (1800 meters) for the Washougal district and pressures of approximately 67 bars (741 meters) in the North Santiam district. These pressure/depth estimates are similar to those calculated for other porphyry districts (Nash, 1976). In addition, the larger size and coarser textures of plutons in the Washougal district indicate that they represent a deeper level of emplacement compared to the plutons of the North Santiam district. However, 740 meters must be considered a minimum depth to mineralization, as the topographic relief between the location of that sample and the highest exposure of rocks affected by mineralization is approximately 800 meters. The similarity of the estimated depth and the relief suggests that a complete section of a pluton related hydrothermal system may be exposed in the North Santiam district.

Depth of cover during mineralization can also be calculated using a combination of the salinity of the fluids and the isotopic temperature estimates based on sulfur isotope fractionation between sulfide mineral pairs. Temperatures based on isotopic fractionation should not need a pressure correction. The difference between isotope temperatures and filling temperatures should approximate the pressure correction for an area. Thus, samples in which this difference was greater than 100°C were not considered for depth calculations. In addition, sulfur isotope temperatures which were

lower than homogenization temperatures were eliminated from consideration because filling temperatures for non-boiling fluids are minimum temperatures. Calculated depths of mineralization for two samples from the Bohemia district range from 800 to 1400 meters (Table 19), very similar to the estimates of depth for the North Santiam (740 meters) and Washougal (1800 meters).

Table 19

Estimates of pressure and depth of mineralization  
based on homogenization temperatures, salinity,  
and sulfur isotope temperatures.

cp = chalcopyrite, gn = galena, py = pyrite, sl = sphalerite.

Sample	T <sub>h</sub> °C	Salinity %	T <sub>34</sub> °C	P (bars)	Depth (meters)
BO-V-1	261-263	13 (cp-gn)	297	70	800
BO-V-8	295	15 (sl-gn)	318	100	1100
		(py-cp)	339	125	1400

## SUMMARY AND CONCLUSIONS

The Cascade Range is a north-south trending volcanic arc which has been active from late Eocene time to the present. The eastern part of the range, the High Cascades, is dominated by Pleistocene to Recent volcanic rocks and stratavolcanoes which have been down-faulted relative to the older Western Cascades. Volcanic flows, pyroclastics, sedimentary rocks, and intrusions of Tertiary age have been gently folded and faulted, and deeply dissected in the Western Cascades subprovince. The mining districts of the Western Cascades and their associated epizonal plutons and locally extensive zones of hydrothermally altered rocks, are roughly parallel to the northerly trend of the Quaternary volcanoes that topographically define the High Cascades.

The volcanic rocks which host much of the mineralization in the Western Cascades range in age from Oligocene (Washougal and Bohemia districts) to Mid-Miocene (North Santiam, Detroit Dam, Quartzville, and Blue River areas). Volcanic rock types are dominated by deposits of volcanoclastic debris, and flows of basalt, basaltic andesite, and andesite. A majority of the flow rocks contain phenocrysts of plagioclase feldspar and augite. Chemical data indicate that the volcanic rocks have calc-alkaline affinities, although they contain more  $\text{CaO}$  and less  $\text{K}_2\text{O}$  than do most continental calc-alkaline suites. Flow rocks from the Bohemia and Blue River districts have higher contents of  $\text{FeO}_t$ ,  $\text{MgO}$ , and  $\text{TiO}_2$  than do those of the more northern

districts. In addition, some flows from the Bohemia district show a slight enrichment of  $\text{FeO}_t$ .

These volcanic rocks are intruded by numerous plutons which are especially common in mining districts and mineralized areas. The plutons range in size from small dikes less than a few centimeters wide to stocks several kilometers in width. Quartz diorite and granodiorite are the most voluminous rock types represented, although diorites, tonalites, and quartz monzonites are also common. Granites are relatively rare. Most of the plutons are porphyritic with groundmass textures that range from aphanitic to finely crystalline. Equigranular phases are uncommon and are usually medium-grained. The common magmatic minerals of these plutons include plagioclase feldspar, pyroxene, hornblende, quartz, biotite, and potassium feldspar. Accessory minerals include apatite, zircon, sphene, and iron-titanium oxides. The magmatic minerals are commonly altered to assemblages which may include several of the following minerals: albite, chlorite, epidote, carbonate, white mica, biotite, potassium feldspar, and clays.

Chemical trends shown by the plutons are similar to those of the volcanic rocks of the region, and they presumably are genetically related. The most obvious difference is that most of the volcanic rocks have less  $\text{SiO}_2$  than the majority of the plutons. Chemical data for plutonic rocks follow more closely the simple calc-alkaline trend than do those for the volcanics, as demonstrated by Harker variation, AFM and NKC diagrams. The plutons of the Bohemia and Blue River

districts have slightly higher contents of  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2$ , and  $\text{MgO}$  at a given content of  $\text{SiO}_2$  than do rocks from other districts, as was previously noted for their associated volcanics. Chemical data portrayed on potash versus silica and alkali versus silica diagrams suggest that the plutons of the Western Cascades more closely resemble those from island arc terrains such as the Caribbean, central British Columbia, and the southwestern Pacific than the cratonic plutons of Bingham, Utah and southern Arizona.

The ages of plutons in the Western Cascades range from 7 to 22 m.y. and are remarkably consistent with those ranging from 6 to 22 m.y. for similar rocks and mineral deposits from the Cascades of central and northern Washington. Similarities in the ages of both primary magmatic and secondary alteration minerals indicate that hydrothermal mineralization is temporally as well as spatially related to the plutons of the Western Cascades, which implies a close genetic relationship.

Within a given district, the largest most complex plutons are generally found at lower elevations. In the Washougal and North Santiam districts, where porphyry mineralization has been discovered, plutons decrease in size and complexity with increasing altitude. Thus larger, composite plutons may underlie the small intrusions now exposed in other mineralized areas.

In the North Santiam district, a porphyritic granodiorite may be closely related to mineralization, and in the Washougal district, late granodiorite and quartz diorite porphyries are closely

associated with breccia pipes and mineralization. Direct associations between mineralization and specific plutons are not readily apparent in the other districts.

Most plutons and their surrounding volcanic host rocks have been fractured and altered. In some districts, breccia pipes are intimately associated with plutons and mineralization. These breccia pipes range from 3 to 100 meters in diameter, and they are surrounded by alteration halos which obscure contacts with the enclosing host rocks. Breccia fragments are usually irregular in shape, and range from 1 mm to 5 cm in diameter. Larger fragments are surrounded by a matrix of smaller clasts and rock flour, and (or) by a cement of quartz, sericite, and tourmaline which have also replaced the breccia fragments. The relative abundance of tourmaline decreases at higher altitudes within individual breccia pipes and within entire districts. Thus, tourmaline-bearing breccia pipes may underlie those brecciated areas which do not contain tourmaline. Three types of breccias have been described in the Western Cascades: matrix-rich, rubble-rich, and shatter breccias. Mineralization is most closely associated with the tourmalinized rubble-rich breccias.

Mineral deposits in the Western Cascades consist of both base metal veins and disseminated pyrite and chalcopyrite mineralization. The veins trend predominantly to the northwest and west, and dip steeply. They are commonly less than 50 centimeters wide. Sphalerite, galena, chalcopyrite, and pyrite are the most abundant sulfides, and quartz is the most common gangue mineral. The relative

amounts of these vein minerals vary within a single district and also between districts. The largest and most persistent veins are found in the Bohemia district. A rough areal zonation of vein minerals has been observed in the Bohemia and North Santiam districts. Veins in the central part of the Bohemia district are larger, more continuous, and contain more sulfides relative to those of the periphery. In the North Santiam district, a central zone characterized by chalcopyrite and specular hematite grades outward through a zone of chalcopyrite and pyrite to an outer zone characterized by sphalerite and galena.

Disseminated mineralization has been reported in the North Santiam, Washougal, and Quartzville districts. In the North Santiam district, pyrite, chalcopyrite, and bornite occur as microveinlets and disseminated blebs in tourmaline-bearing breccia pipes and replace ferromagnesian minerals of the microdiorite host. In the northern part of the Washougal district, disseminated mineralization is associated with the Black Jack and Miners Queen breccia pipes. Disseminated pyrite and occasional grains of chalcopyrite are found in the Dry Gulch area of the Quartzville district.

Propylitic alteration is the most widespread evidence of hydrothermal activity in the Western Cascades. It is characterized by chlorite, epidote, calcite, albite, quartz, sericite, magnetite, pyrite, and zeolites, and halos of this alteration type surround the intrusions and all known occurrences of base and precious metal veins. Argillic and phyllic alteration assemblages are associated with shear zones, faults, breccia pipes, and large veins. These

assemblages are characterized by quartz, sericite, kaolinite, and sometimes tourmaline. Many breccia pipes are altered to an assemblage containing tourmaline, quartz, sericite, and hematite, that is accompanied by pyrite, chalcopyrite and sometimes bornite.

Areas of potassic alteration are exposed in the Bohemia, North Santiam, and Washougal districts. This assemblage is characterized by biotite, potassium feldspar, tourmaline, quartz, sericite, magnetite, and pyrite. Much of the biotite has been subsequently altered to chlorite. Potassic alteration is generally exposed at lower elevations and is centrally located in these districts.

The concentration of trace metals varies among districts of the Western Cascades. Samples from the Washougal district are higher in copper and molybdenum relative to those of the other districts, whereas samples from the North Santiam district contain more copper, lead, and zinc. The South Umpqua district contains anomalously high concentrations of lead, zinc, and possibly molybdenum. By comparison, the Glacier Peak deposit is characterized by copper, molybdenum, and possibly zinc whereas the Margaret deposit is defined by copper and molybdenum.

Porphyry-type mineralization in the North Santiam and Washougal districts is indicated by a cluster of points near the copper apex on ternary Cu-Pb-Zn diagrams. In addition, many samples from all districts of the Western Cascades, except the Washougal district, contain subsequential amounts of copper and zinc and smaller quantities of lead.

Samples of the Glacier Peak deposit differ from those of the Western Cascades, the Washougal district, and the Margaret deposit in their higher concentrations of Ag, Zn, Ba, V, As, Sb, and W. The presence of these elements may reflect a thicker and more evolved continental crust below the Glacier Peak deposit. Samples of potassic and phyllic types of alteration may have been enriched in Ni, Ag, Cu, Mo, Sn, and Pb, and depleted in Mn, Zr, and Y.

The  $\delta^{34}\text{S}$  values of sulfides from the Cascades are similar to those of many other porphyry districts of the cordillera. Isotopic compositions range from -5.1 to +5.0 permil, with an average of 1.7 permil. The variation of  $\delta^{34}\text{S}$  values within one district is as great as that within the entire sample suite. However, pyrite and chalcopyrite from vein samples may be slightly depleted in  $^{34}\text{S}$  relative to the same minerals from breccias and disseminated occurrences. The preponderance of values near 0 permil probably indicate a magmatic source for the sulfur. Temperature estimates calculated from these data indicate that vein-type mineralization in the Western Cascades ranged from 200 to 500°C. However, a temperature of 675°C was recorded for sulfide pairs in single samples of porphyry-type mineralization from the Glacier Peak deposit and the Washougal district. These high temperatures are similar to those reported for porphyry deposits elsewhere (Nash, 1976; Eastoe, 1979).

The fluid inclusion data from samples of veins, breccia pipes, and altered rocks in the Western Cascades are similar to those obtained from porphyry-type deposits elsewhere. Inclusions of

moderately salinity (type I) are found in veins and in association with propylitic and phyllic alteration. They homogenize at temperatures from 167 to 319°C and range in salinity from nearly 0 to 18 weight percent NaCl equivalent. Many of these inclusions are secondary and formed during multiple episodes of fracturing and annealing. Dawsonite (?), rhombohedral carbonate, anhydrite, and hematite are daughter minerals observed in type I inclusions. Vapor-rich (Type II) inclusions are associated with type I and III inclusions in breccia pipes of the Western Cascades, and boiling of the hydrothermal fluid can be documented in two samples. The halite-bearing (type III) inclusions (> 30 weight percent NaCl), characteristic of porphyry mineralization, are associated with breccia pipes and plutonic rocks which are altered to a potassic assemblage. Filling temperatures for these inclusions range from 246° to 386°C, and they are consistent with those from the lower part of the thermal range for porphyry environments. Daughter minerals include halite, sylvite, rhombohedral carbonate, anhydrite, and hematite, which are typically associated with porphyry-type mineralization.

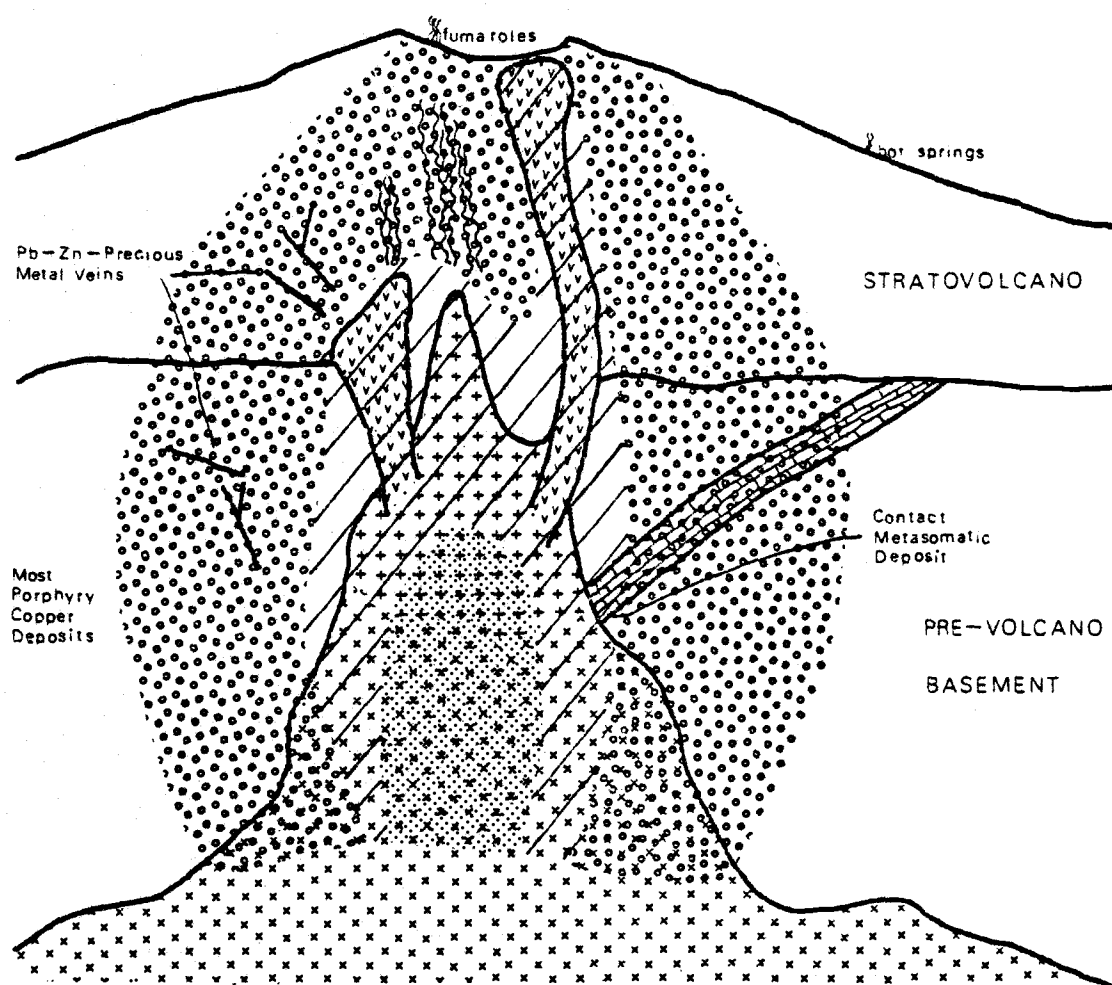
The approximate depth of cover during mineralization is estimated from the fluid inclusion data at 1800 m and 740 m for the Washougal and North Santiam districts, respectively. That for the Bohemia district, based on the data provided from fluid salinities and sulfur isotope temperatures, is estimated to have been approximately 800 to 1400 meters. These depths are compatible with other estimates of porphyry-type mineralization. In addition, the

relatively shallow depth to mineralization in the North Santiam district, as compared to the present relief in that area, suggests that a complete section of a pluton-related hydrothermal system is now exposed.

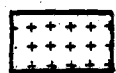
Sillitoe (1973) has proposed a theoretical model for the "tops and bottoms" of porphyry copper deposits as is illustrated in Figure 34. This diagram shows the relationships between volcanism, plutonism, and porphyry mineralization which previously have been hypothesized by Burnham (1967), Lowell and Guilbert (1970), Rose (1970, Norton and Cathles (1973), and others. By comparing the mining districts of the Western Cascades to the Glacier Peak and Margaret porphyry deposits of the Washington Cascades, it is evident that all depth levels of porphyry mineralization are represented.

The Cascade deposits are similar to those of most other porphyry provinces in that they are located within a volcanic arc that is subparallel to the adjacent continental margin. In addition, each of the districts in the Cascades is located at the junction of two structural trends: the generally north-trending gentle folds which parallel the range, and the east-west or northwest trending faults and (or) shear zones. Throughout the world, similar structural intersections may have been responsible for providing the channelways for plutonic rocks and their associated hydrothermal solutions (Titley and Beane, 1981).

Various geologic and metallogenetic features of mineral deposits and districts of the Cascade Range are summarized in Table 20 and in



### ROCK TYPES



PORPHYRY STOCK



PHANERITIC  
GRANODIORITE



HYDROTHERMAL  
INTRUSION BRECCIA

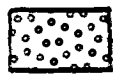


LIMESTONE

### ALTERATION



SILICIFICATION  
ADVANCED ARGILLIC



PROPYLITIC



SERICITIC



POTASSIC

Figure 34. A hypothetical cross section of a typical, simple porphyry copper deposit and its relationship to the other types of hydrothermal mineral deposits (after Sillitoe, 1973).

Table 20. Rock types, pluton sizes and textures, breccias, mineralization, metals, and fluid inclusions of mineralized areas in the Cascades listed in order of apparent level of exposure

HIGH LEVEL	ROCK TYPE	PLUTON SIZE	TEXTURE	BRECCIAS	MINERALI- ZATION	METALS	FLUID INCLUSION TYPES	HIGH LEVEL
South Umpqua, Fall Creek?	V	D,pa		sz	dp,vn	Cu, Zn, pm		South Umpqua, Fall Creek?
Blue River	V	D,P; pa-pfg		sz,vn	dp,vn	Cu, Pb, Zn, pm	I, II	Blue River
Quartzville	V	D,P; pg-pfg-fge		sz,vn,r+t	dp,vn	Cu, Pb, Zn, pm	I,II	Quartzville
? Detroit Dam ?	V = P	D,S; pfg		sz	dp			?Detroit Dam ?
Bohemia	V = P	D,P,S; pfg		m,r,s +t	vn,dp,bx	Cu, Pb, Zn,pm	I,II,III	Bohemia
North Santiam	V = P	D,P,S; pfg-efg		m,r,s, +t +mn	vn,dc,bx	Cu, Mo Cu, Pb, Zn, pm	I,II,III	North Santiam
Washougal	P, B?	D,P,S; pfg-s		m,r,s +t +mn	dc,bx,vn	Cu,Mo	I,II,III	Washougal
Margaret	P, B	D,S; pfg-s		? +t	dc,vn	Cu,Mo	I,II,III	Margaret
Glacier Peak	P, B	B,D; pfg-emg		to north	dc,vn	Cu,Mo	I,II,III	Glacier Peak

DEEP LEVEL

DEEP LEVEL

V = volcanic	D dike	sz = shear zone	dp = dis. pyrite	Pm = precious metals
P = plutonic	P plug	vn = vein	vn = vein	
B = pre-volcano basement	S stock	r = rubble-rich	dc = dis. copper	
	B batholith	m = matrix-rich	bx = breccia	
	P porphyritic	s = shatter		
	a aphanitic	+t = tourmaline- bearing		
	fg fine grained	+mn = mineralized		
	e equigranular			
	s seriate			
	mg medium grained			

Figures 35-38. The "bottom" of a Cascade porphyry system is exemplified by the Glacier Peak deposit. Copper and molybdenum mineralization is associated with porphyry dikes that crosscut medium-grained quartz diorite and gneiss. All the volcanic rocks, which may have been associated with the batholith and porphyry dikes, have been eroded from the area immediately adjacent to the deposit. Mineralization consists of veinlets and disseminations of chalcopyrite, pyrite, pyrrhotite, and molybdenite. Sulfide minerals are associated with a potassic assemblage which includes sericite, quartz, chlorite, and carbonate minerals, in addition to potassium feldspar and biotite. As in all mineralized areas of the Cascades, mineralization is strongly controlled by structures; contacts between altered fractured host rocks and unaltered country rocks are sharp. Metal zoning is weakly developed within the deposit. At a depth of 1000 feet, the "orebody" passes transitionally into a low grade core with subeconomic metal values. At this deep level, the halos of pyrite and propylitic alteration are small, and breccia pipes, if originally present, have been eroded as they do not crop out over distances of less than one mile from the main orebody.

The Margaret deposit represents a slightly higher level of mineralization in the idealized Cascade hydrothermal system. Host intrusions are of stock size, and are fine- to medium-grained seriate in texture. This pluton of Miocene age intrudes a "basement" of Eocene volcanic rocks. Mineralization is again dominated by copper and minor molybdenum in the form of veinlets and disseminations. At

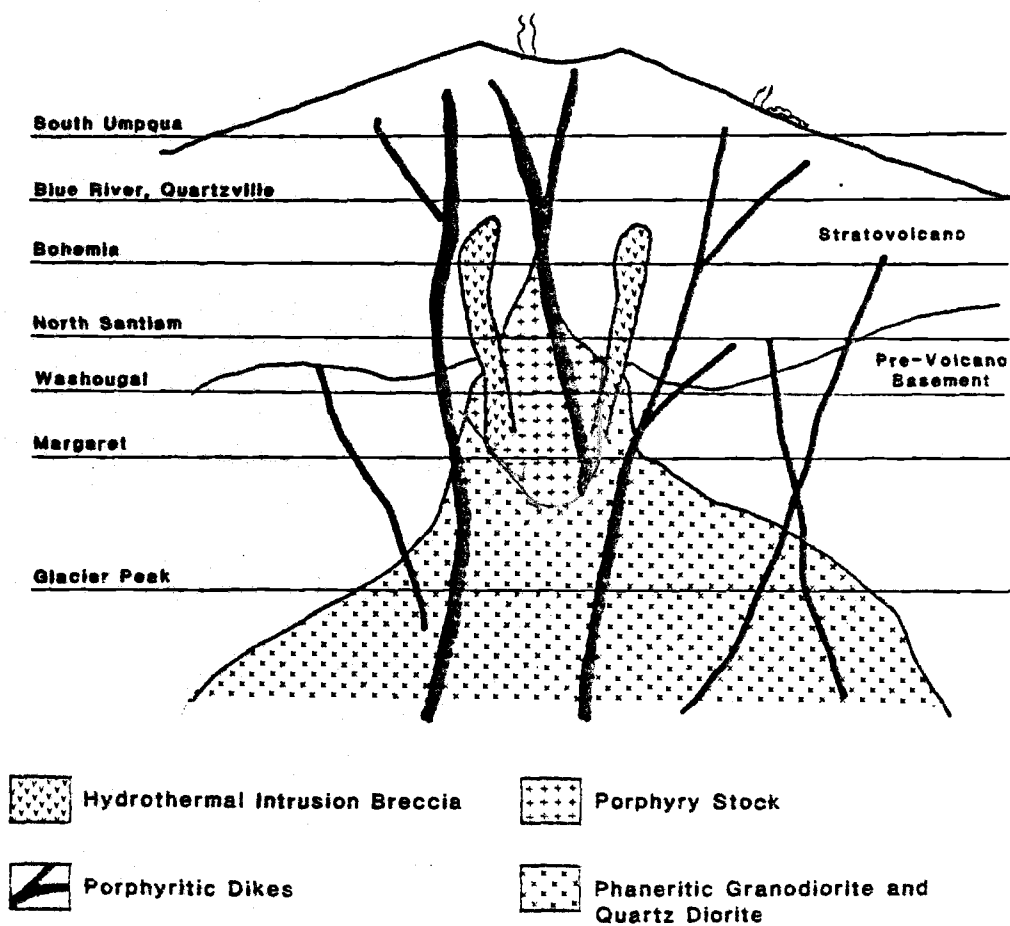


Figure 35. Hypothetical cross section of a Cascade porphyry system: rock types.

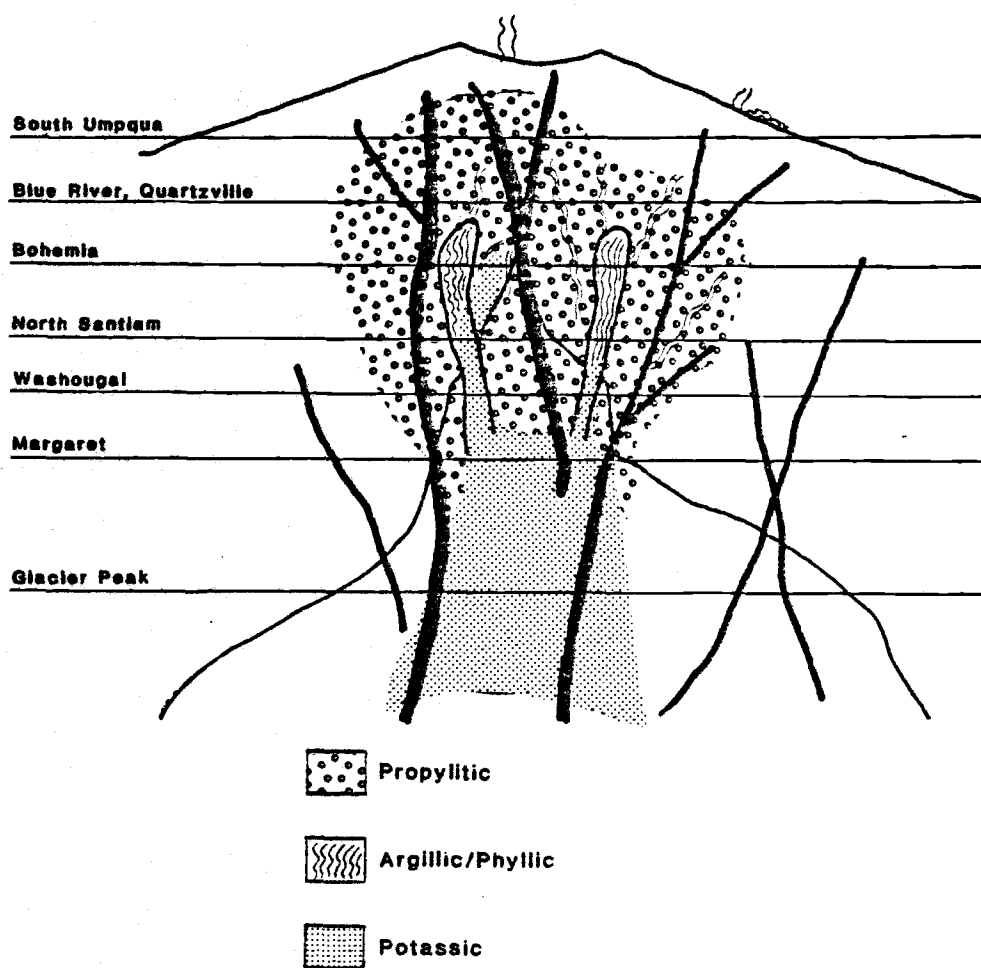


Figure 36. Hypothetical cross section of a Cascade porphyry system: alteration.

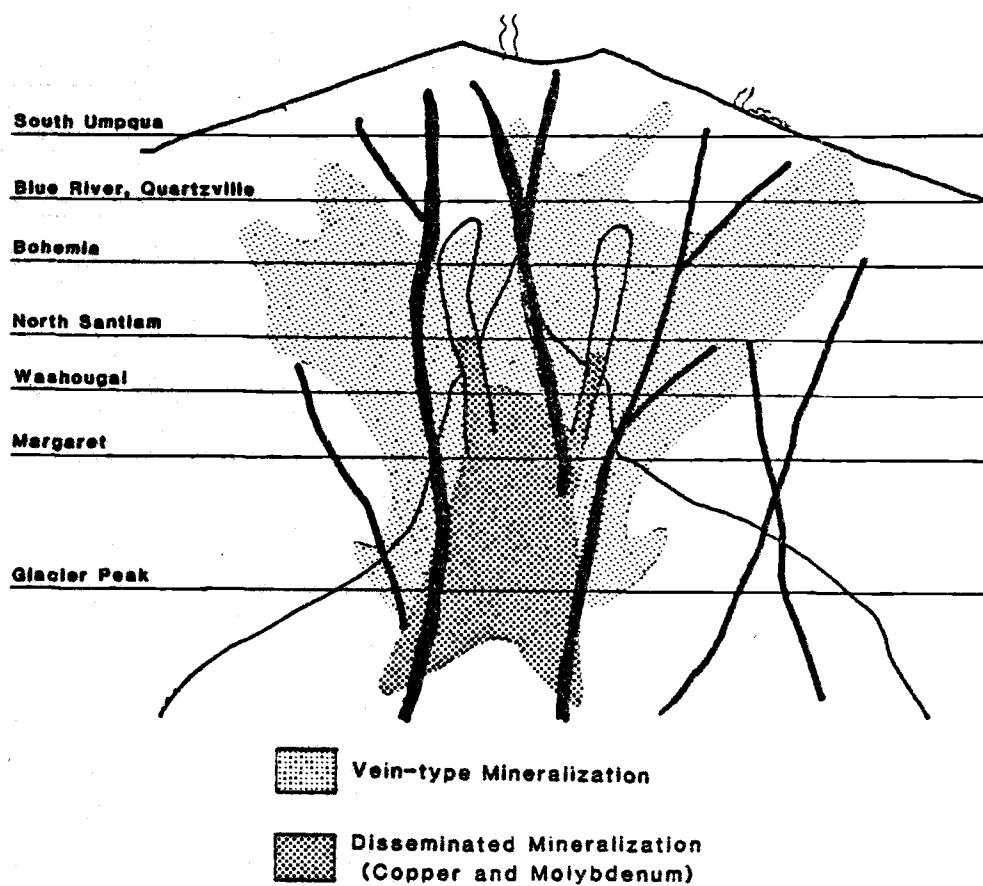


Figure 37. Hypothetical cross section of a Cascade porphyry system: mineralization.

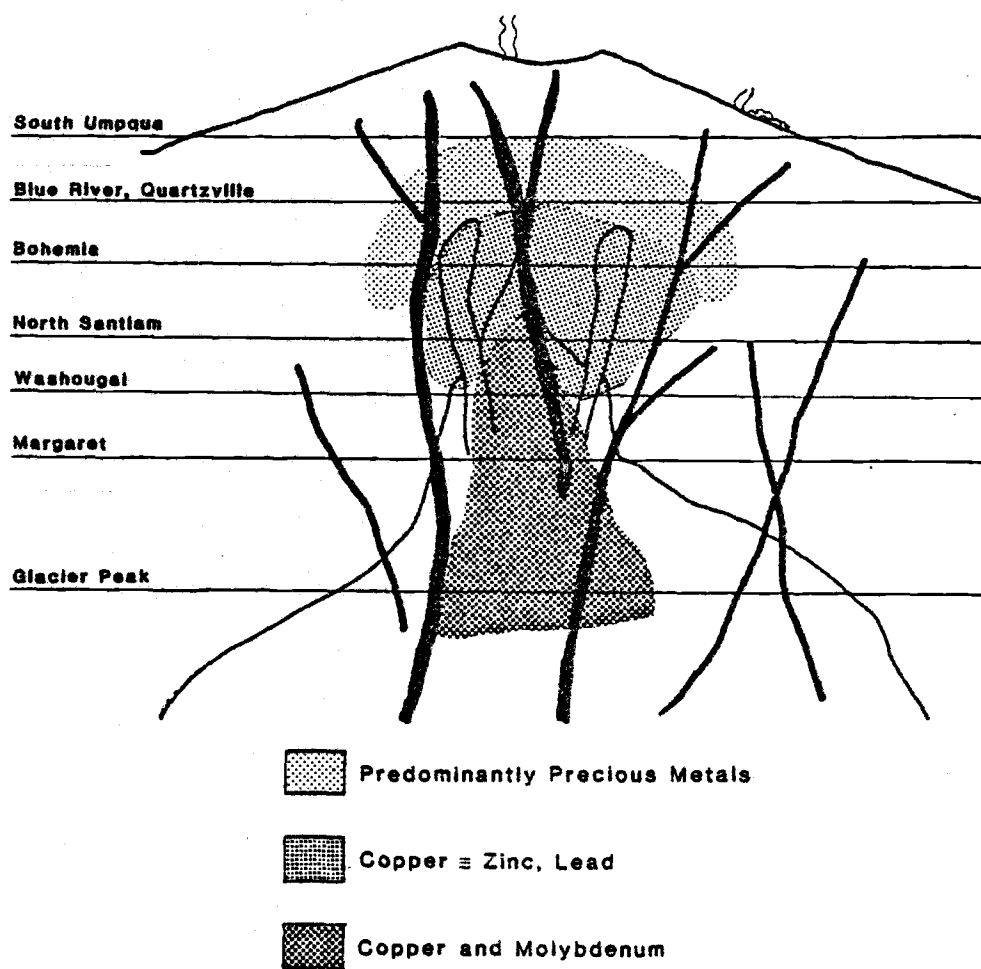


Figure 38. Hypothetical cross section of a Cascade porphyry system: potential metals production.

this level, the metal-bearing potassic core grades outward to phyllic and propylitic zones and downward into a low grade or "barren" potassic zone. Alteration minerals associated with ore grade mineralization include quartz, carbonate, chlorite (retrograde from biotite), and sometimes tourmaline. Metal and sulfide mineral zonations within the deposit as presently defined are negligible. Breccia pipes are not present at the deposit, although a large area of tourmaline-bearing breccia crops out to the north.

In the Washougal and North Santiam districts to the south, erosion has exposed copper mineralization in breccia pipes and diamond drilling programs have revealed disseminated porphyry-type mineralization at depth. Host rocks include large stock-sized plutons (larger in the Washougal district) which at least partly intrude contemporary volcanic rocks. Copper and molybdenum mineralization are present in both districts. However, the North Santiam district has abundant copper-, zinc-, and lead-bearing veins as well. Both districts have areas of potassic alteration coincident with ore-bearing breccia pipes. This assemblage includes tourmaline, biotite, potassium feldspar, quartz, and chlorite in addition to chalcopyrite, bornite, pyrite, and molybdenite. Phyllic/argillic alteration is superimposed on the large propylitic halo and on the central potassic core. Depth estimates from fluid inclusion data indicate that porphyry mineralization in the Washougal district took place at a depth of 1800 m and that in the North Santiam district at about 740 m. The latter depth is essentially identical to the

present relief in this district, suggesting a complete exposure from the level of breccia-associated porphyry mineralization upward to well-developed vein systems which display district-wide metal zoning. These are covered by weakly altered volcanic rocks which are intruded by dikes and small quartz veins.

The Bohemia district exemplifies the level of well-developed vein-type mineralization. The veins of this district cut propylitically altered intrusions and volcanic rocks. Plutons range in size from dikes to the Champion stock. The dominant metallic vein minerals are pyrite, chalcopyrite, sphalerite, and galena. These are associated with gangue quartz, carbonates, barite, clays, and specular hematite. Vein minerals are crudely zoned on a district-wide scale, although zoning is complicated by the effects of paragenesis and topography. Several tourmaline-bearing breccia pipes crop out and have been altered to an assemblage containing quartz, sericite, and tourmaline. One small area of potassic alteration is coincident with a geochemical anomaly for copper and molybdenum and is adjacent to a chalcopyrite-bearing breccia pipe. In addition, haltite-bearing (Type III) fluid inclusions have been identified in samples of plutonic rock from this area, which is also the location of the most magmatic oxygen isotope values reported by Taylor (1971) for this district. Undoubtedly, porphyry-type mineralization is present a short distance below the surface in this area.

Plutonic rocks are smaller and there is a decrease in the quantity of sulfide minerals in veins in the Blue River and Quartzville

districts. Propylitically altered volcanic rocks are crosscut by quartz and carbonate veins and are intruded by numerous porphyritic dikes and plugs. Phyllic/argillic alteration is localized along faults and shear zones. Outcrops of tourmaline-bearing breccia pipes have not been located in these districts, although fragments of such breccias have been found as float in the Quartzville district.

The South Umpqua and Fall Creek districts represent the uppermost exposures of porphyry-type deposits in the Western Cascades. In these districts, volcanic rocks are intruded by small porphyritic dikes, and the most widespread evidence of mineralization is the ubiquitous propylitic alteration. Veins are localized in poorly defined shear zones. Sulfide minerals are rare, although disseminated pyrite is an important constituent of the propylitic assemblage in these districts. The presence of tourmaline associated with anomalous copper and molybdenum in one sample from the South Umpqua district indicates the possibility of porphyry mineralization at depth.

The position of the Detroit Dam area in this idealized Cascade porphyry system is not readily apparent. Although the pluton exposed is fairly large, associated mineralization is represented only by sparse veins of quartz and widespread propylitic alteration. Thus, the Detroit Dam area may be a system exposed at a very high level, and the plutons associated with the hydrothermal event may lie at some depth below the surface. To the contrary, the area may be

representative of a "barren" porphyry system -- one in which the metals were not present in the hydrothermal solutions.

According to this model, the Western Cascades have several potential sites of porphyry-type copper-molybdenum mineralization. Only time (erosion), or venture capital, (a few well-placed deep drill holes) will verify this hypothesis.

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## APPENDICES

## APPENDIX 1

Locations of volcanic and plutonic rock samples from the Western Cascades of Oregon and southern Washington for which analyses of major oxide and trace element constituents are given in Appendices 2 and 3 (samples listed by number, rock type, and public-land division; more specific locations may be obtained from the appropriate references cited).

Topographic base maps and locations of samples are with respect to U.S. Geological Survey 15 Minute Series as follows:

- Washougal District, Washington
  - Lookout Mountain Quadrangle, Washington
  - Bridal Veil Quadrangle, Oregon and Washington
  - Yacolt Quadrangle, Washington

- North Santiam District, Oregon
  - Battle Ax Creek Quadrangle, Oregon
  - Mill City Quadrangle, Oregon

- Detroit Dam area, Oregon
  - Detroit Quadrangle, Oregon
  - Quartzville Quadrangle, Oregon

- Quartzville District, Oregon
  - Quartzville Quadrangle, Oregon

- Blue River District, Oregon
  - Blue Riven Quadrangle, Oregon

- Bohemia District, Oregon
  - Fairview Peak Quadrangle, Oregon

- South Umpqua District, Oregon
  - Red Butte Quadrangle, Oregon

### Volcanic Rocks

1. Basaltic andesite; ridge north of Silver Star Mtn., SW $\frac{1}{4}$  sec. 7, T. 3 N., R. 5 E.
2. Mafic flow; center N $\frac{1}{2}$ NW $\frac{1}{4}$  sec. 27, T. 3 N., R. 5 E.
3. Basaltic andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 2, T. 3 N., R. 5 E.
4. Andesite; SW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 24, T. 8 S., R. 5 E.
5. Andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 26, T. 8 S., R. 5 E.
6. Dacite; SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 29, T. 8 S., R. 5 E.
7. Quartz latite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 27, T. 8 S., R. 5 E.
8. Quartz latite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 27, T. 8 S., R. 5 E.
9. Basaltic andesite; center sec. 7, T. 10 S., R. 5 E.
10. Andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 19, T. 10 S., R. 5 E.
11. Dacite dike; center S $\frac{1}{2}$ , sec. 18, T. 10 S., R. 5 E.
12. Dacite; SE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 7, T. 10 S., R. 5 E.
13. Basalt; NE $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 29, T. 11 S., R. 4 E.
14. Andesite; SE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 26, T. 11 S., R. 4 E.
15. Andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 23, T. 11 S., R. 4 E.
16. Andesite; NW $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 16, T. 11 S., R. 4 E.
17. Andesite; SW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 13, T. 11 S., R. 4 E.
18. Andesite; SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 12, T. 12 S., R. 4 E.
19. Andesite; center SE $\frac{1}{4}$  sec. 28, T. 11 S., R. 4 E.
20. Andesite; NE cor. NW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 26, T. 11 S., R. 4 E.
21. Andesite; NW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 34, T. 11 S., R. 4 E.
22. Dacite; NW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 14, T. 11 S., R. 4 E.
23. Rhyodacite; E. side NE $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 13, T. 11 S., R. 4 E.

24. Basaltic andesite dike; SW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 28, T. 15 S., R. 4 E.
25. Basaltic andesite; center SE $\frac{1}{4}$  sec. 32, T. 15 S., R. 4 E.
26. Basaltic andesite; center NE $\frac{1}{4}$  sec. 28, T. 15 S., R. 4 E.
27. Basaltic andesite; SE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 31, T. 15 S., R. 4 E.
28. Basaltic andesite; SW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 21, T. 15 S., R. 4 E.
29. Dacite; SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 5, T. 15 S., R. 4 E.
30. Basalt porphyry; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 18, T. 23 S., R. 1 E.
31. Basalt porphyry; SW $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 11, T. 23 S., R. 1 E.
32. Basalt porphyry; SW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.
33. Shoshonite porphyry dike; SW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
34. Andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
35. Andesite; NE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.
36. Andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
37. Andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
38. Andesite porphyry; NE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 13, T. 23 S., R. 1 E.
39. Andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
40. Andesite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 1, T. 23 S., R. 1 E.
41. Dacite porphyry flow; SW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 2, T. 23 S., R. 1 E.
42. Dacite porphyry intrusion; SE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.

#### Plutonic Rocks

- WA-1    Quartz diorite; NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 11, T. 4 N., R. 5 E.
- WA-2    Quartz diorite; N $\frac{1}{2}$ SW $\frac{1}{4}$  sec. 17, T. 4 N., R. 5 E.
- WA-3    Diorite; E $\frac{1}{2}$ SW $\frac{1}{4}$  sec. 28, T. 4 N., R. 5 E.
- WA-4    Quartz diorite; SW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 26, T. 4 N., R. 5 E.

- WA-5 Quartz diorite; NE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 33, T. 4 N., R. 5 E.
- WA-6 Granodiorite porphyry; SW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 33, T. 4 N., R. 5 E.
- WA-7 Granite aplite; SW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 33, T. 4 N., R. 5 E.
- WA-8 Granodiorite; SW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 33, T. 4 N., R. 5 E.
- WA-9 Quartz diorite porphyry; NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 34, T. 4 N., R. 5 E.
- WA-10 Diorite; SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 35, T. 4 N., R. 5 E.
- WA-11 Granodiorite; 2000 ft elevation in north central part of unsurveyed area, T. 3 N., R. 5 E.
- WA-12A Granodiorite porphyry; Miner's Queen prospect, Miner's Creek, T. 4 N., R. 5 E.
- WA-12B Quartz diorite porphyry; Miner's Queen prospect, Miner's Creek, T. 4 N., R. 5 E.
- WA-13 Granodiorite; 1940 ft elevation west fork of Copper Creek, T. 4 N., R. 5 E.
- WA-14 Quartz diorite porphyry; 2080 ft elevation west fork of Copper Creek, T. 3 N., R. 5 E.
- WA-15 Granodiorite; 3600 ft elevation, NE ridge of Little Baldy Mountain, T. 3 N., R. 5 E.
- WA-16 Quartz diorite; 2000 ft elevation, east of sharp west turn in West Fork River, SW of Little Baldy Mountain, T. 3 N., R. 5 E.
- WA-17 Quartz monzodiorite; Center N $\frac{1}{2}$ NW $\frac{1}{4}$  sec. 29, T. 3 N., R. 5 E.
- WA-18 Quartz diorite; Center N $\frac{1}{2}$ NE $\frac{1}{4}$  sec. 29, T. 3 N., R. 5 E.
- WA-19 Diorite; N corner intersection of sec. 28 and sec. 27, T. 3 N., R. 5 E.
- WA-20 Granite aplite; SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 29, T. 3 N., R. 5 E.
- WA-21 Intrusive andesite; NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 33, T. 3 N., R. 5 E.
- WA-22 Granodiorite; Larch Mountain SW $\frac{1}{4}$  sec. 26, T. 3 N., R. 4 E.
- NS-1 Granodiorite; SW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 18, T. 8 S., R. 5 E.
- NS-2 Granodiorite; NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 19, T. 8 S., R. 5 E.

- NS-4 Granodiorite; Center  $N\frac{1}{2}SW\frac{1}{4}$  sec. 28, T. 8 S., R. 5 E.
- NS-5 Granodiorite;  $SW\frac{1}{4}NW\frac{1}{4}$  sec. 27, T. 8 S., R. 5 E.
- NS-6 Diorite;  $NW\frac{1}{4}NE\frac{1}{4}$  sec. 27, T. 8 S., R. 5 E.
- NS-7 Diorite;  $SW\frac{1}{4}NW\frac{1}{4}$  sec. 27, T. 8 S., R. 5 E.
- NS-10 Diorite;  $SE\frac{1}{4}NW\frac{1}{4}$  sec. 32, T. 8 S., R. 5 E.
- NS-11 Granodiorite;  $SE\frac{1}{4}NW\frac{1}{4}$  sec. 31, T. 8 S., R. 5 E.
- NS-12 Granodiorite;  $SE\frac{1}{4}SE\frac{1}{4}$  sec. 32, T. 8 S., R. 5 E.
- NS-13 Microdiorite; sec. 29, T. 8 S., R. 5 E.
- NS-14 Microdiorite; sec. 29, T. 8 S., R. 5 E.
- NS-15 Microdiorite; sec. 29, T. 8 S., R. 5 E.
- DD-3 Granite aplite; center  $E\frac{1}{2}SW\frac{1}{4}$  sec. 18, T. 10 S., R. 5 E.
- DD-14 Granodiorite;  $SE\frac{1}{4}SW\frac{1}{4}$  sec. 18, T. 10 S., R. 5 E.
- DD-16A Quartz diorite (altered); center  $SW\frac{1}{4}$  sec. 18, T. 10 S., R. 5 E.
- DD-88 Granodiorite; center  $E\frac{1}{2}$  sec. 26, T. 10 S., R. 4 E.
- DD-101 Granodiorite;  $SW\frac{1}{4}NW\frac{1}{4}$  sec. 19, T. 10 S., R. 5 E.
- DD-T8-4 Granodiorite;  $SW\frac{1}{4}NW\frac{1}{4}$  sec. 17, T. 10 S., R. 5 E.
- DD-T12-3 Granodiorite (altered);  $SW\frac{1}{4}SW\frac{1}{4}$  sec. 18, T. 10 S., R. 5 E.
- QV-1 Granite aplite; 3.2 km. west of district
- QV-2 Quartz monzonite;  $SW\frac{1}{4}SW\frac{1}{4}$  sec. 13, T. 11 S., R. 4 E.
- QV-3 Diorite dike;  $NW\frac{1}{4}NE\frac{1}{4}$  sec. 23, T. 11 S., R. 4 E.
- QV-4 Quartz monzonite (rhyolite?); center, sec. 22, T. 11 S., R. 4 E.
- QV-6 Diorite sill;  $NE\frac{1}{4}SW\frac{1}{4}$  sec. 23, T. 11 S., R. 4 E.
- QV-7 Granodiorite;  $SW\frac{1}{4}SW\frac{1}{4}$  sec. 36, T. 11 S., R. 4 E.
- QV-8 Granite;  $SW\frac{1}{4}SE\frac{1}{4}$  sec. 15, T. 12 S., R. 4 E.

- NR-1 Granite; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 3, T. 17 S., R. 3 E.
- BR-1 Diorite; SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 22, T. 15 S., R. 4 E.
- BR-2 Granodiorite; NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 27, T. 15 S., R. 4 E.
- BR-3 Silicic dike; NW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 27, T. 15 S., R. 4 E.
- BR-3X Silicic dike; NW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 27, T. 15 S., R. 4 E.
- BR-4 Granodiorite; NE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 28, T. 15 S., R. 4 E.
- BR-5 Diorite; NW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 29, T. 15 S., R. 4 E.
- BR-6 Quartz diorite; SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 32, T. 15 S., R. 4 E.
- BR-7 Diorite; NW $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 32, T. 15 S., R. 4 E.
- BR-8 Granodiorite; SE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 32, T. 15 N., R. 4 E.
- BR-9 Granodiorite; NW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 32, T. 15 N., R. 4 E.
- BR-10 Quartz diorite; NE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 31, T. 15 N., R. 4 E.
- B0-1 Quartz monzonite porphyry; NE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 1, T. 23 S., R. 1 E.
- B0-2 Quartz diorite; NW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 1, T. 23 S., R. 1 E.
- B0-3 Quartz diorite; NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 1, T. 23 S., R. 1 E.
- B0-4 Granodiorite; NE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 1, T. 23 S., R. 1 E.
- B0-5 Quartz diorite porphyry; SW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.
- B0-6 Quartz diorite porphyry; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.
- B0-7 Quartz diorite porphyry; NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.
- B0-8 Quartz diorite porphyry; SW $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.
- B0-9 Quartz diorite porphyry; NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 13, T. 23 S., R. 1 E.
- B0-10 Quartz diorite porphyry; NW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 13, T. 23 S., R. 1 E.
- B0-11 Quartz diorite porphyry; SW $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 13, T. 23 S., R. 1 E.
- B0-12 Quartz diorite porphyry; NW $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 13, T. 23 S., R. 1 E.
- B0-13 Quartz diorite porphyry; NE $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.

- B0-14     Quartz diorite porphyry; SE $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
- B0-15     Quartz diorite porphyry; SE $\frac{1}{4}$ NE $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
- B0-16     Quartz diorite porphyry; NE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
- B0-17     Quartz diorite porphyry; NE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
- B0-18     Quartz diorite porphyry; NW $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
- B0-19     Granodiorite; SE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 14, T. 23 S., R. 1 E.
- B0-20     Quartz diorite porphyry; SE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.
- B0-21     Quartz diorite porphyry; SE $\frac{1}{4}$ SE $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.
- SU-18     Quartz diorite; 1480 ft elevation east of the South Umpqua River along road south of Zinc Creek, sec. 23, T. 29 S., R. 1 W.

## APPENDIX 2

Major Oxide and Trace Element Analyses for  
Volcanic Rocks of the Western Cascades

## Explanation

Samples 1-3 are from the Washougal District (Shepard, 1979; Schriener, 1978).

Samples 4-8 are from the North Santiam District (Olson, 1978).

Samples 9-12 are from the Detroit Dam area (McLean, unpubl. data).

Samples 13-23 are from the Quartzville District (Munts, 1978).

Samples 24-29 are from the Blue River District (Storch, 1978).

Samples 30-42 are from the Bohemia District (Schaubs, 1978).

## APPENDIX 2 (continued)

	1	2	3	4	5	6	7	8
	<u>S78-73b</u>	<u>S78-30</u>	<u>172</u>	<u>SS-3-A</u>	<u>SS-7</u>	<u>FA-DP</u>	<u>RD-2</u>	<u>RD-1</u>
SiO2	52.8	54.3	56.0	58.7	60.9	61.8	62.8	77.0
TiO2	1.0	1.3	1.0	0.95	0.75	0.80	0.80	0.15
Al2O3	17.2	16.8	17.8	16.6	18.9	16.8	17.5	13.1
Fe2O3	1.9	2.1	---	---	---	---	---	---
FeO	5.5	5.5	8.9	8.5	6.3	5.6	4.3	1.85
MnO	0.15	0.14	---	---	---	---	---	---
MgO	4.8	3.9	4.0	3.8	2.3	2.8	2.2	0.3
CaO	9.7	8.1	7.8	6.1	5.4	5.3	4.9	2.3
Na2O	2.4	3.0	3.8	3.4	4.0	3.5	4.1	0.4
K2O	0.5	0.6	0.6	1.48	1.05	2.05	1.40	3.0
H2O+	1.2	1.4	---	---	---	---	---	---
P2O5	---	---	---	---	---	---	---	---
Total	<u>97.15</u>	<u>97.2</u>	<u>100.0</u>	<u>99.53</u>	<u>95.11</u>	<u>98.65</u>	<u>98.1</u>	<u>98.0</u>
Cu	130	120	280	60	35	40	10	45
Mo	<1	1	3	1	<1	<1	<1	2
Pb	10	10	10	35	10	15	40	205
Zn	30	50	25	80	60	55	60	525
Ag	0.6	0.4	0.4	0.6	0.3	0.4	0.6	1.0

	9	10	11	12	13	14	15	16
	<u>DD-116</u>	<u>DD-75</u>	<u>DD-53</u>	<u>DD-48</u>	<u>X7</u>	<u>1328</u>	<u>1501</u>	<u>1462</u>
SiO2	52.2	58.3	61.2	64.2	51.67	54.66	55.31	55.77
TiO2	1.1	0.90	0.87	1.1	1.07	0.99	1.03	1.46
Al2O3	16.8	17.2	15.9	14.9	17.38	15.97	18.45	15.66
Fe2O3	4.3	2.3	1.9	2.4	7.96	8.01	6.99	9.81
FeO	3.0	3.7	3.6	3.7	---	---	---	---
MnO	0.12	0.12	0.11	0.096	0.12	0.13	0.12	0.16
MgO	4.8	3.3	2.9	1.6	4.99	5.66	3.46	3.55
CaO	7.7	6.6	4.2	3.8	10.79	9.47	8.09	6.96
Na2O	3.2	3.5	3.8	3.6	2.70	2.93	3.28	3.71
K2O	0.76	0.69	1.9	2.2	0.57	1.60	0.35	0.74
H2O+	2.8	1.3	1.4	0.6	---	---	---	---
P2O5	---	---	---	---	0.28	0.39	0.23	0.31
Total	<u>96.78</u>	<u>97.91</u>	<u>97.78</u>	<u>98.196</u>	<u>97.53</u>	<u>99.81</u>	<u>97.31</u>	<u>97.82</u>
Cu	60	40	55	35	---	---	---	---
Mo	2	1	<1	2	---	---	---	---
Pb	11	12	9	8	---	---	---	---
Zn	30	50	40	25	---	---	---	---
Ag	0.5	0.6	0.4	0.3	---	---	---	---

## APPENDIX 2 (continued)

	17 X3	18 1294	19 1236	20 2021	21 1245	22 1611	23 X2	24 28.21
SiO2	56.9	57.18	58.39	59.87	63.9	64.4	72.0	53.0
TiO2	1.20	1.00	0.93	0.90	1.20	0.90	0.35	1.20
Al2O3	19.5	18.04	17.24	17.06	16.6	16.6	14.2	18.8
Fe2O3	----	6.63	6.68	6.25	----	----	----	----
FeO	6.9	----	----	----	6.6	4.9	2.8	8.2
MnO	----	0.12	0.12	0.11	----	----	----	----
MgO	3.2	4.49	3.39	2.91	2.7	1.8	0.4	5.9
CaO	7.0	7.95	6.69	6.63	1.2	3.1	1.0	9.3
Na2O	3.7	3.0	4.51	3.80	6.8	4.8	5.1	3.1
K2O	0.55	0.66	0.74	1.54	0.45	2.90	3.15	0.25
H2O+	----	----	----	----	----	----	----	----
P2O5	----	0.19	0.19	0.22	----	----	----	----
Total	98.95	99.26	98.88	99.29	99.45	99.40	99.0	99.75

Cu	----	----	----	----	----	----	----	----
Mo	----	----	----	----	----	----	----	----
Pb	----	----	----	----	----	----	----	----
Zn	----	----	----	----	----	----	----	----
Ag	----	----	----	----	----	----	----	----

	25 32.24	26 28.29	27 31.5	28 21.7	29 5.2	30 1-13	31 2-21	32 5-16
SiO2	53.0	54.3	54.7	57.2	61.2	49.2	49.5	49.6
TiO2	1.10	1.10	1.10	0.95	1.55	1.60	1.30	1.25
Al2O3	18.3	18.8	17.8	18.2	15.2	19.2	17.2	17.9
Fe2O3	----	----	----	----	----	----	----	----
FeO	7.8	7.8	8.0	7.0	8.1	11.3	9.8	10.0
MnO	----	----	----	----	----	----	----	----
MgO	5.2	5.2	5.9	4.2	2.5	3.8	7.3	7.5
CaO	8.8	8.8	8.5	8.2	4.5	10.4	9.3	10.2
Na2O	3.8	3.0	3.9	3.5	4.3	2.8	2.8	2.3
K2O	0.40	0.15	0.25	0.40	2.0	0.45	0.40	0.55
H2O+	----	----	----	----	----	----	----	----
P2O5	----	----	----	----	----	----	----	----
Total	98.40	99.15	100.15	99.65	99.35	98.75	97.60	99.30

Cu	40	35	----	35	60	----	----	----
Mo	<1	<1	----	<1	<1	----	----	----
Pb	13	6	----	5	20	----	----	----
Zn	55	40	----	40	55	----	----	----
Ag	0.7	0.7	----	0.7	0.7	----	----	----

	33	34	35	36	37	38	39	40
	<u>2-29</u>	<u>1-14c</u>	<u>8-2</u>	<u>1-14b</u>	<u>1-14d</u>	<u>3-17</u>	<u>1-14</u>	<u>3-18</u>
SiO2	53.4	53.7	54.3	55.5	55.5	55.8	56.3	59.7
TiO2	1.00	1.15	1.20	1.15	1.70	1.30	1.65	1.30
Al2O3	15.4	16.2	16.9	16.4	15.4	16.4	15.8	15.1
Fe2O3	----	----	----	----	----	----	----	----
FeO	9.8	9.6	9.5	9.3	8.8	8.3	10.0	10.5
MnO	----	----	----	----	----	----	----	----
MgO	8.1	6.8	5.6	6.0	4.6	4.6	4.6	3.6
CaO	7.7	8.2	8.8	8.2	7.2	8.9	7.6	4.8
Na2O	2.6	3.4	2.8	3.0	3.5	2.7	3.4	3.7
K2O	2.35	0.90	0.65	1.05	1.55	1.30	1.35	0.75
H2O+	----	----	----	----	----	----	----	----
P2O5	----	----	----	----	----	----	----	----
Total	<u>100.35</u>	<u>99.95</u>	<u>99.75</u>	<u>100.60</u>	<u>98.25</u>	<u>99.30</u>	<u>100.70</u>	<u>99.45</u>

	41	42
	<u>1-15</u>	<u>2-25</u>
SiO2	71.5	71.6
TiO2	0.45	0.55
Al2O3	14.6	15.1
Fe2O3	----	----
FeO	3.5	3.5
MnO	----	----
MgO	0.9	0.7
CaO	2.1	2.0
Na2O	4.5	4.2
K2O	2.55	2.40
H2O+	----	----
P2O5	----	----
Total	<u>100.10</u>	<u>100.10</u>

## APPENDIX 3

Major Oxide and Trace Element Chemical Analyses and Normative  
Mineral Contents for Plutonic Rocks  
of the Western Cascades

## Explanation

WA indicates samples from the Washougal district.  
NS indicates samples from the North Santiam district.  
DD indicates samples from the Detroit Dam area.  
QV indicates samples from the Quartzville district.  
BR indicates samples from the Blue River district.  
NR indicates samples from the Nimrod stock.  
BO indicates samples from the Bohemia district.  
SU indicates samples from the South Umpqua district.

Samples WA-1, 4, 5, 7, 10, 12A, 12B, 13, 22 from Schriener (1978).  
Samples WA-14 through WA-21 from Shepard (1979).  
Samples NS-1 through NS-15 from Olson (1978).  
Samples DD-3, 14, 16A, 88, 101 from McLean (1980).  
Samples DDT78-4 and T12-3 from Pungrassami (1970).  
Samples QV-1, 2, 3, 6, 7, 8 from Muntz (1978).  
Samples BR-1, 2, 3X, 4, 6, 8, 9, 10 from Storch (1978).  
Samples BO-1 through 21 from Schaub (1978).  
Samples WA-6 and WA-8 are reanalysis of samples analyzed by Schriener (1978).  
Samples SU-18 from Ness (1978).

All others were analyzed by Dr. E. M. Taylor and R. L. Lightfoot, Oregon State University for all major oxides except  $\text{Fe}_2\text{O}_3$  and  $\text{FeO}$  which were analyzed by Skyline Labs, Denver, Colorado. Trace elements were performed by Chemical and Mineralogical Services, Salt Lake City, Utah.

APPENDIX 3 (continued)

	WA-1 RC-4	WA-2	WA-3	WA-4 134	WA-5 118	WA-6 034A	WA-7 034B	WA-8 035	WA-9	WA-10 082	WA-11
SiO2	58.2	51.6	52.2	56.5	58.1	68.1	76.0	63.4	56.4	52.6	65.0
TiO2	1.0	0.95	1.70	1.0	0.8	0.40	0.4	0.55	0.94	1.3	0.75
Al2O3	16.7	20.4	17.3	19.2	18.0	14.9	11.0	16.8	18.5	18.2	15.6
Fe2O3	3.10	3.30	5.50	3.90	2.80	1.6	1.20	2.50	3.70	3.30	3.70
FeO	4.30	4.80	5.60	3.30	3.70	2.7	1.00	1.80	3.70	5.10	2.40
MgO	3.8	4.4	5.3	3.5	4.0	2.4	0.4	2.8	3.7	5.5	1.8
CaO	5.8	11.0	8.9	8.6	6.6	3.7	1.7	4.7	6.5	8.5	4.4
Na2O	4.0	2.8	2.5	4.3	4.2	3.7	3.8	4.2	4.2	3.9	3.8
K2O	1.0	0.70	0.35	0.6	1.2	3.2	4.2	2.35	1.40	0.6	2.45
Total	97.9	100.05	99.35	100.9	99.4	100.7	99.7	99.1	99.05	99.0	99.9
Cu	75	120	25	95	55	100	40	12	125	45	----
Mo	2	2	1	2	1	2	3	2	2	1	----
Pb	8	11	30	7	7	5	18	5	35	11	----
Zn	20	50	60	55	35	12	12	12	65	30	----
Ag	0.3	0.3	<.3	0.3	0.7	0.4	0.7	0.3	<.3	0.3	----
Q	11.5	2.5	8.7	6.7	8.2	22.0	35.9	15.9	6.5	0.7	21.6
C	----	----	----	----	----	----	----	----	----	----	----
or	5.9	4.1	2.1	3.5	7.1	18.9	24.8	13.9	8.3	3.5	14.5
ab	33.8	23.7	21.2	36.4	35.5	31.3	32.2	35.5	35.5	33.0	32.2
an	24.7	41.0	34.9	31.3	26.7	14.6	0.6	20.0	27.5	30.4	18.3
di	3.3	11.3	7.3	9.0	4.8	3.0	2.5	2.6	3.8	9.4	2.8
hy	11.6	10.0	12.7	5.7	10.8	7.5	----	6.1	9.6	13.7	3.3
mt	4.5	4.8	8.0	5.7	4.1	2.3	1.7	3.6	5.4	4.8	5.4
hm	----	----	----	----	----	----	----	----	----	----	----
il	1.9	1.8	3.2	1.9	1.5	0.8	0.8	1.0	1.8	2.5	1.4
ap	----	----	----	----	----	----	----	----	----	----	----
other	----	----	----	----	----	----	1.8 <sup>1</sup>	----	----	----	----
Total	97.2	99.2	98.1	100.2	98.7	100.4	98.5	98.6	98.4	98.0	99.5

1. wollastonite

## APPENDIX 3 (continued)

	WA-12A	WA-12B	WA-13	WA-14	WA-15	WA-16	WA-17	WA-18	WA-19	WA-20	WA-21
	<u>061-B</u>	<u>309</u>	<u>205</u>	<u>S78-81b</u>	<u>S78-94</u>	<u>S78-124</u>	<u>S78-120</u>	<u>S78-70</u>	<u>S78-97</u>	<u>S78-116</u>	<u>S78-5</u>
S102	66.5	59.1	65.2	58.9	65.9	60.3	61.8	58.3	58.5	67.2	54.9
TiO2	0.45	1.0	0.7	0.8	0.8	0.9	1.0	1.1	0.6	0.6	1.2
Al2O3	16.7	16.1	16.6	16.8	14.9	17.2	15.9	17.0	15.9	14.5	16.1
Fe2O3	2.40	3.30	4.60	2.4	1.6	2.9	2.4	3.2	2.7	1.3	1.7
FeO	2.00	3.40	1.10	4.2	2.6	3.4	3.4	3.1	4.5	2.3	5.8
MgO	1.5	4.3	1.8	3.6	1.9	3.2	2.7	3.6	3.7	1.8	4.9
CaO	4.2	6.6	4.2	4.0	3.9	6.2	5.1	6.6	6.8	3.9	7.8
Na2O	4.5	5.9	4.4	4.4	3.5	4.0	3.6	4.3	3.2	3.6	2.3
K2O	2.0	0.4	2.3	1.7	2.5	0.9	1.9	1.4	1.6	2.5	1.3
Total	<u>100.25</u>	<u>100.1</u>	<u>100.9</u>	<u>96.8</u>	<u>97.6</u>	<u>99.0</u>	<u>97.80</u>	<u>97.60</u>	<u>97.50</u>	<u>97.70</u>	<u>96.00</u>
Cu	1670	670	50	390	75	18	125	50	95	95	130
Mo	3	2	2	2	2	1	1	2	4	3	2
Pb	8	6	10	25	20	8	7	20	5	4	25
Zn	15	25	20	60	45	30	30	65	60	55	75
Ag	0.5	0.4	0.3	0.3	0.4	0.3	0.3	0.4	<.2	0.3	0.7
Q	21.0	4.7	19.0	9.5	23.5	14.6	17.4	9.0	13.0	24.9	10.1
C	-----	-----	-----	0.4	-----	-----	-----	-----	-----	-----	-----
or	11.8	2.4	13.6	10.0	14.8	5.3	11.2	8.3	9.5	14.8	7.7
ab	38.1	49.9	37.2	37.2	29.6	33.8	30.5	36.4	27.1	30.5	19.5
an	19.5	16.3	18.8	19.8	17.6	26.3	21.6	22.9	24.3	16.0	29.8
di	1.1	13.0	1.6	-----	1.4	3.6	3.0	7.7	7.7	2.7	7.3
hy	4.2	6.4	3.7	15.1	6.3	8.8	8.1	6.8	10.5	5.4	16.2
mt	3.5	4.8	1.5	3.5	2.3	4.2	3.5	4.6	3.9	1.9	2.5
hm	-----	-----	3.6	-----	-----	-----	-----	-----	-----	-----	-----
il	0.9	1.9	1.3	1.5	1.5	1.7	1.9	2.1	1.1	1.1	2.3
ap	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
other	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Total	<u>100.1</u>	<u>99.4</u>	<u>100.3</u>	<u>97.0</u>	<u>97.0</u>	<u>98.3</u>	<u>97.2</u>	<u>97.8</u>	<u>97.1</u>	<u>97.3</u>	<u>95.4</u>

APPENDIX 3 (continued)

	WA-22	NS-1	NS-2	NS-4	NS-5	NS-6	NS-7	NS-10	NS-11	NS-12	NS-13
	SS-1	M-9	M-1	Y-4	O-9	O-1	O-2	P-4	KA-1	P-10	2-2003
SiO2	61.7	64.0	65.5	62.0	65.0	55.0	55.4	54.7	63.73	64.90	52.0
TiO2	0.8	0.65	0.65	0.67	0.65	1.2	1.3	1.2	0.67	0.54	1.5
Al2O3	17.3	17.4	15.6	16.0	16.3	19.3	19.6	19.1	16.5	15.44	21.3
Fe2O3	5.20	2.80	3.20	2.20	3.00	3.50	3.30	3.60	2.01	1.63	---
FeO	1.10	2.10	1.40	2.40	2.10	4.80	4.70	4.20	2.58	2.74	9.8 <sup>2</sup>
MgO	2.7	2.7	2.30	2.7	1.9	4.0	3.8	4.8	2.0	1.83	3.6
CaO	5.3	4.6	3.8	5.2	5.8	6.6	6.4	7.9	4.17	3.63	5.8
Na2O	4.3	3.3	4.1	3.3	3.6	3.8	4.1	3.5	3.94	3.21	3.7
K2O	2.0	2.1	2.2	1.1	1.6	0.15	0.72	0.37	2.01	2.99	1.65
Total	100.40	99.65	98.75	95.57	99.95	98.35	99.32	99.37	97.61	96.91	99.35
Cu	50	55	35	45	30	590	170	100	50	30	340
Mo	2	<1	<1	<1	<1	<1	1	<1	<1	1	5
Pb	10	30	30	41	25	40	30	40	40	25	8
Zn	20	65	55	585	75	130	100	255	55	50	30
Ag	0.3	0.4	0.6	0.3	0.8	0.6	0.8	0.6	1.0	0.7	1.0
Q	14.0	22.2	21.4	22.3	23.2	9.5	6.7	7.5	20.0	22.8	---
C	---	1.3	---	---	---	0.9	0.4	---	0.5	0.6	---
or	11.8	12.4	13.0	6.5	9.5	0.9	4.3	2.2	11.9	17.7	---
ab	36.4	27.9	34.7	27.9	30.5	32.2	34.7	29.6	33.3	27.2	---
an	22.0	22.8	17.7	25.6	23.6	32.7	31.7	35.3	20.0	17.4	---
di	3.3	---	0.9	0.2	4.1	---	---	3.1	---	---	---
hy	5.2	7.2	5.3	8.1	3.1	13.9	13.2	13.2	7.1	7.4	---
mt	1.2	4.1	2.6	3.2	4.3	5.1	4.8	5.2	2.9	2.4	---
lm	4.4	---	1.4	---	---	---	---	---	---	---	---
il	1.5	1.2	1.2	1.3	1.2	2.3	2.5	2.3	1.3	1.0	---
ap	---	---	---	---	---	---	---	---	0.3	0.2	---
other	---	---	---	---	---	---	---	---	---	---	---
Total	99.8	99.1	98.2	95.1	99.5	97.5	98.3	98.4	97.3	96.7	---

2. Total iron reported as FeO

APPENDIX 3 (continued)

	NS-14 1-2013	NS-15 1-1944	DD-3	DD-14	DD-16A	DD-88	DD-101	DD-T8-4	DDT12-3	QV-1 X-12	QV-2 I-13B
S102	56.3	60.5	76.5	65.5	67.8	64.7	65.2	55.41	65.88	75.62	71.90
TiO2	1.3	1.1	0.24	0.64	0.63	0.81	0.78	0.82	0.47	0.91	1.05
Al2O3	18.1	16.0	12.1	15.1	15.3	15.7	14.9	17.87	16.25	11.46	12.88
Fe2O3	-----	-----	0.89	2.2	<0.01	1.60	1.90	2.78	2.04	0.99	2.00
FeO	8.5 <sup>2</sup>	7.4 <sup>2</sup>	1.1	3.0	1.1	3.7	2.70	3.89	2.32	0.52	1.00
MgO	2.4	3.0	0.3	2.0	2.1	2.9	2.2	5.47	1.66	0.62	0.68
CaO	6.1	4.0	1.2	2.9	4.4	4.4	4.0	7.14	3.24	1.64	2.19
Na2O	4.9	2.8	3.6	3.2	2.3	3.8	4.2	3.30	2.64	0.42	3.62
K2O	1.55	2.25	3.7	2.2	0.51	1.9	1.6	1.19	2.99	7.02	4.29
Total	99.15	97.05	99.63	96.74	94.14	98.97	97.48	97.87	97.63	99.20	99.61
			7	4	6	2	3	1	5		
Cu	1010	5100	20	110	35	55	15	55	165	15	5
Mo	7	13	2	1	1	<1	2	1	<1	4	<1
Pb	6	8	10	6	12	15	7	10	20	40	<10
Zn	35	45	13	14	60	25	18	70	60	25	30
Ag	1.0	1.0	0.3	0.4	0.5	0.4	0.3	<0.2	<0.2	<0.3	<1
Q	----	----	37.8	27.6	38.9	19.4	21.8	7.1	28.7	41.4	29.0
C	----	----	----	2.2	3.0	----	----	----	3.0	0.2	----
or	----	----	21.9	13.0	3.0	11.2	9.5	7.0	17.7	41.5	25.4
ab	----	----	30.5	27.1	19.5	32.2	35.5	27.9	22.3	3.6	30.6
an	----	----	5.9	14.4	21.8	20.2	17.1	30.4	15.6	8.1	6.2
di	----	----	----	----	----	1.3	2.2	3.2	----	----	3.3
hy	----	----	1.7	7.7	6.3	10.9	6.6	16.1	6.1	1.5	0.2
mt	----	----	1.3	3.2	----	2.3	2.8	4.0	3.0	----	0.4
hm	----	----	----	----	----	----	----	----	----	1.0	1.7
il	----	----	0.5	1.2	1.2	1.5	1.5	1.6	0.9	1.2	2.0
ap	----	----	----	----	----	----	----	0.4	0.2	----	0.1
other	----	----	----	----	----	----	----	----	----	0.3 <sup>3</sup>	----
Total	----	----	99.6	96.4	93.7	99.0	97.0	97.7	97.5	98.8	98.9

2. Total iron reported as FeO

3. Rutile

## APPENDIX 3 (continued)

	QV-3	QV-4	QV-6	QV-7	QV-8	NR-1	BR-1	BR-2	BR-3	BR-3X	BR-4
	1198		1454	1350	4047		22.8a	27.1		27.6	28.38
S102	51.47	78.0	60.52	63.18	68.11	74.9	60.8	68.4	65.8	70.3	65.0
Ti02	0.96	0.2	0.91	0.77	0.58	0.35	0.80	0.45	1.20	0.95	0.75
Al203	17.45	11.4	18.28	15.83	14.04	13.2	16.7	15.6	14.3	17.9	16.0
Fe203	1.30	0.30	4.20	2.50	1.60	1.10	3.20	1.50	2.20	1.40	2.90
FeO	5.90	0.44	1.80	3.60	1.70	0.85	2.10	1.60	3.80	0.89	1.80
MgO	6.04	0	2.48	3.06	1.19	0	3.7	1.5	1.2	0.5	2.2
CaO	8.17	0.3	4.82	4.85	2.52	1.3	5.4	3.9	3.9	0.2	3.8
Na2O	3.44	0.9	3.99	2.42	3.93	4.1	4.0	3.3	3.9	1.9	3.8
K2O	1.53	5.75	1.84	2.42	3.44	3.55	1.60	2.35	2.55	4.05	2.55
Total	96.27	97.29	98.84	98.63	97.11	99.35	98.3	98.6	98.85	98.09	98.8
Cu	75	45	----	200	----	15	30	14	80	60	60
Mo	<1	4	----	1	----	2	<1	<1	<1	5	<1
Pb	20	105	----	30	----	25	7	5	15	11	5
Zn	115	15	----	115	----	10	35	30	70	45	30
Ag	1.0	0.5	----	<1	----	<0.3	0.3	0.3	<.3	0.7	0.3
Q	----	49.9	16.1	23.3	24.6	34.4	14.6	28.8	22.0	41.9	21.1
C	----	3.1	1.4	0.9	----	0.2	----	0.5	----	10.0	0.1
or	9.0	34.0	10.9	14.3	20.3	21.0	9.5	13.9	15.1	23.9	15.1
ab	29.1	7.6	33.8	20.5	33.3	34.7	33.8	27.9	33.0	16.1	32.2
an	27.7	1.5	22.6	22.8	10.5	6.4	22.9	19.3	14.0	1.0	18.9
di	9.6	----	----	----	1.1	----	3.0	----	4.5	----	----
hy	9.7	0.2	6.2	11.1	3.4	0.1	7.8	4.7	4.0	1.2	5.5
mt	1.9	0.4	3.5	3.6	2.3	1.6	4.4	2.2	3.2	0.1	3.6
hm	----	----	1.8	----	----	----	0.1	----	----	1.3	0.4
fl	1.8	0.4	1.7	1.5	1.1	0.7	1.5	0.9	2.3	1.8	1.4
ap	0.4	----	0.5	0.5	0.2	----	----	----	----	----	----
other	6.6	----	----	----	----	----	----	----	----	----	----
Total	95.8	97.1	98.5	98.5	96.8	99.1	97.6	98.2	98.1	97.3	98.3

4. olivine

## APPENDIX 3 (continued)

	BR-5	BR-6	BR-7	BR-8	BR-9	BR-10	BO-1	BO-2	BO-3	BO-4	BO-5
	<u>58.4</u>	<u>32.5</u>	<u>61.6</u>	<u>32.32</u>	<u>32.30</u>	<u>31.8</u>	<u>8-32</u>	<u>2-22</u>	<u>3-12</u>	<u>8-18</u>	<u>1-24</u>
S102	58.4	59.64	61.6	62.3	65.61	58.8	65.55	66.5	55.8	70.5	61.0
T102	1.15	0.79	1.00	1.00	0.93	1.10	0.76	0.80	0.95	0.80	0.85
Al2O3	17.0	18.79	18.2	16.8	15.42	17.4	15.14	16.2	17.7	14.4	16.0
Fe2O3	5.90	3.69	2.60	2.30	2.89	3.40	2.81	2.00	4.00	2.20	2.80
FeO	2.20	1.98	4.00	3.50	2.60	4.10	2.54	2.40	3.9	1.50	3.70
MgO	4.0	2.85	3.5	3.4	2.07	3.8	1.63	2.7	5.0	1.0	4.2
CaO	6.0	6.35	1.9	2.8	2.33	4.4	4.27	3.0	7.6	4.2	5.5
Na2O	4.4	3.88	3.0	3.5	3.79	3.5	3.67	2.1	3.7	3.5	3.2
K2O	0.55	1.03	2.95	3.35	2.05	6.9	2.03	2.70	1.25	0.95	1.55
Total	<u>99.6</u>	<u>97.97</u>	<u>98.75</u>	<u>98.95</u>	<u>97.69</u>	<u>97.40</u>	<u>98.40</u>	<u>98.40</u>	<u>99.90</u>	<u>99.05</u>	<u>98.80</u>
Cu	25	40	55	55	25	16	70	20	30	95	20
Mo	<1	<1	1	<1	<1	<1	3	1	<1	20	1
Pb	5	8	6	10	14	15	30	3	15	11	18
Zn	55	25	60	40	40	35	35	35	75	55	65
Ag	0.3	0.3	0.3	0.3	0.3	1.0	0.4	0.3	0.7	0.3	0.7
Q	12.0	14.8	21.2	15.9	26.6	17.8	24.3	32.2	6.1	35.4	16.9
C	----	----	6.6	2.3	2.8	2.7	----	4.4	----	----	----
or	3.3	6.1	17.4	19.8	12.1	5.3	12.0	16.0	7.4	5.6	9.2
ab	37.2	32.8	25.4	29.6	32.1	29.6	31.1	17.8	31.3	29.6	27.1
an	25.0	30.8	9.4	13.9	11.4	21.8	18.8	14.9	28.0	20.8	24.7
di	3.7	0.5	----	----	----	----	1.2	----	7.7	----	2.1
hy	8.2	6.9	12.3	11.3	6.1	12.4	4.9	8.2	11.1	2.5	12.6
mt	3.8	4.4	3.8	3.3	4.2	4.9	4.1	2.9	5.8	2.5	4.1
hm	3.3	0.7	----	----	----	----	----	----	----	0.5	----
il	2.2	1.5	1.9	1.9	1.8	2.1	1.4	1.5	1.8	1.5	1.6
ap	----	----	----	----	----	----	0.3	----	----	----	----
other	----	----	----	----	----	----	----	----	----	----	----
Total	<u>98.7</u>	<u>98.5</u>	<u>96.1</u>	<u>98.0</u>	<u>97.1</u>	<u>96.6</u>	<u>98.1</u>	<u>97.9</u>	<u>99.2</u>	<u>98.4</u>	<u>98.3</u>

APPENDIX 3 (continued)

	B0-6	B0-7	B0-8	B0-9	B0-10	B0-11	B0-12	B0-13	B0-14	B0-15	B0-16
	8-1	6-1	9-24	14-7	8-7	6-8	7-10	9-10	1-29	3-15	5-15
S102	64.3	62.5	60.5	63.4	64.8	63.5	59.3	64.8	61.0	60.8	66.3
T102	0.85	0.90	1.00	0.95	0.90	0.90	1.10	0.80	0.90	1.00	0.80
Al2O3	16.0	16.1	16.2	16.0	15.7	15.9	16.2	15.6	16.5	16.4	15.4
Fe2O3	3.10	3.20	3.50	3.60	2.80	3.50	3.50	3.20	3.70	3.10	2.50
FeO	2.80	3.10	3.40	2.60	2.80	2.60	3.30	2.40	3.00	3.10	2.60
MgO	3.1	3.1	3.6	3.3	2.5	2.8	3.9	2.8	4.0	3.6	2.2
CaO	5.2	5.7	4.6	4.3	4.5	5.1	5.5	3.9	5.4	5.4	3.9
Na2O	3.4	3.5	3.2	3.4	4.1	3.9	3.5	3.8	2.8	3.7	3.6
K2O	1.70	1.85	2.70	1.90	2.10	1.85	1.60	2.45	2.50	2.05	2.55
Total	100.45	99.95	98.70	99.45	100.20	100.05	97.90	99.75	99.8	99.15	99.85
Cu	20	25	30	25	25	25	20	16	19	25	25
Mo	1	1	<1	<1	<1	<1	<1	1	1	<1	1
Pb	7	8	30	6	4	18	6	7	75	5	12
Zn	60	35	150	120	35	65	55	95	430	55	50
Ag	0.3	0.3	0.3	1.0	0.3	1.4	0.8	0.7	0.3	0.7	0.3
Q	21.6	18.0	15.0	21.4	19.1	18.8	14.5	20.2	16.9	14.1	22.9
C	----	----	----	0.5	----	----	----	----	----	----	----
or	10.0	10.9	16.0	11.2	12.4	10.9	9.5	14.4	14.8	12.1	15.1
ab	28.8	29.6	27.1	28.8	34.7	33.0	29.6	32.2	23.7	31.3	30.5
an	23.4	22.8	21.9	21.3	18.2	20.4	23.8	18.3	25.1	22.1	18.3
di	1.9	4.4	0.8	----	3.3	3.8	2.8	0.8	1.4	3.7	0.8
hy	8.0	7.2	10.3	8.5	6.0	5.6	9.8	7.0	10.3	8.7	6.5
mt	4.5	4.6	5.1	5.2	4.1	5.1	5.1	4.6	5.4	4.5	3.6
hm	----	----	----	----	----	----	----	----	----	----	----
il	1.6	1.7	1.9	1.8	1.7	1.7	2.1	1.5	1.7	1.9	1.5
ap	----	----	----	----	----	----	----	----	----	----	----
other	----	----	----	----	----	----	----	----	----	----	----
Total	99.8	99.2	98.1	98.7	99.5	99.3	97.2	99.0	99.3	98.4	99.2

## APPENDIX 3 (continued)

	B0-17	B0-18	B0-19	B0-20	B0-21	SU-18
	4-15	3-29	4-29	1-4	3-5	
SiO <sub>2</sub>	60.0	51.6	60.5	64.0	57.6	53.20
TiO <sub>2</sub>	1.05	1.30	1.30	0.90	1.0	0.99
Al <sub>2</sub> O <sub>3</sub>	16.9	18.9	17.9	16.2	16.9	19.84
Fe <sub>2</sub> O <sub>3</sub>	3.30	3.90	3.80	3.40	3.20	3.97
FeO	3.70	5.20	5.50	2.50	4.40	4.37
MgO	4.8	5.4	1.0	2.3	4.8	2.81
CaO	4.9	8.9	5.4	5.1	6.6	9.29
Na <sub>2</sub> O	3.4	3.4	4.3	4.1	3.7	3.04
K <sub>2</sub> O	1.70	0.95	2.15	1.65	1.20	0.77
Total	99.75	99.55	101.85	100.15	99.4	98.28

Cu	25	19	16	25	50	35
Mo	<1	1	<1	<1	<1	<1
Pb	6	6	5	7	9	25
Zn	30	55	40	65	60	25
Ag	0.3	0.7	0.7	1.0	1.0	1.0

Q	14.2	0.5	11.8	19.6	9.2	8.1
C	0.6	----	----	----	----	----
or	10.0	5.6	12.7	9.8	7.1	4.6
ab	28.8	28.8	36.4	34.7	31.3	25.7
an	24.3	33.5	23.2	20.9	26.0	38.2
di	----	8.5	3.0	3.4	5.4	5.7
hy	14.3	13.6	5.8	4.4	13.1	7.6
mt	4.8	5.7	5.5	4.9	4.6	5.8
lm	----	----	----	----	----	----
il	2.0	2.5	2.5	1.7	1.9	1.9
ap	----	----	----	----	----	0.3
other	----	----	----	----	----	----
Total	99.0	98.7	100.9	99.4	98.6	97.9

## APPENDIX 4

Descriptions, locations, and ages of samples from the Western Cascades dated by the potassium-argon method (see Power and others, 1981, for analytical data and more complete discussion)

- WA-11 Washougal district, Skamania County, Washington (2000 ft elevation near Black Ledge prospect, north central part of unsurveyed portion of T. 3 N., R. 5 E.,  $45^{\circ}46'43''$  N.,  $122^{\circ}02'29''$  W.); relatively unaltered granodiorite; whole rock; age  $19.6 \pm 0.7$  m.y.
- WA-058A Washougal district, Skamania County, Washington (1680 ft elevation in Copper Creek near Black Jack prospect, north central part of unsurveyed portion of T. 3 N., R. 5 E.,  $45^{\circ}46'20''$  N.,  $122^{\circ}12'$  W.); altered clasts of granodiorite in breccia pipe and completely replaced by quartz, sericite, tourmaline, and pyrite; whole rock; age  $19.0 \pm 0.7$  m.y.
- NS-11 North Santiam district, Marion County, Oregon (3520 ft elevation, SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec; 31, T. 8 S., R. 5 E.,  $44^{\circ}50'24''$  N.,  $122^{\circ}14'40''$  W.); relatively unaltered granodiorite; magmatic hornblende; age  $13.4 \pm 0.9$  m.y.
- BR-6 Blue River district, Lane County, Oregon (4200 ft elevation on ridge northeast of Gold Hill, SE $\frac{1}{4}$ NW $\frac{1}{4}$  sec. 32, T. 15 S., R. 4 E.,  $44^{\circ}13'09''$  N.,  $122^{\circ}21'23''$  W.); relatively unaltered quartz diorite; whole rock; age  $13.4 \pm 1.2$  m.y.
- BO-7 Bohemia district, Lane County, Oregon (3720 ft elevation in NE $\frac{1}{4}$ SW $\frac{1}{4}$  sec. 12, T. 23 S., R. 1 E.,  $43^{\circ}35'36''$  N.,  $122^{\circ}37'45''$  W.); relatively unaltered quartz diorite porphyry; whole rock; age  $21.7 \pm 0.8$  m.y.

## APPENDIX 5

GEOLOGY OF THE  
GLACIER PEAK AND MARGARET PORPHYRY DEPOSITS

The mines and mining districts of this dissertation have been repeatedly compared to the Glacier Peak and Margaret porphyry deposits in the Washington Cascades. However, published information about these two deposits is not readily available. Therefore, this appendix briefly summarizes the geology of both deposits.

Glacier Peak Porphyry Deposit

The information presented in this summary was obtained directly from the exploration files of Bear Creek Mining Company, Spokane, Washington; from the wilderness appraisal by Grant (1982); and from core samples provided by Bear Creek. Special thanks must be extended to R. C. Babcock and P. R. Fikkan of the Bear Creek Mining Company for their generosity in sharing this information.

The Glacier Peak porphyry deposit is located on Miners Ridge in the Glacier Peak Wilderness Area, Snohomish County, Washington, about 30 air miles east of Darrington (Figure 1). Mineralization was discovered in the district before the turn of the century, and Bear Creek delineated the porphyry deposit in the 1950's.

Mineralization probably exceeds 30 million tons of about 0.7% copper, with additional molybdenum and possible by-products of tungsten, silver, and gold (Grant, 1982). Glacier Peak is one of the

largest ore deposits in the state of Washington. However, a number of factors inhibit development, such as the difficult access, problems of avalanche control, snow removal, and the surrounding wilderness area.

The Glacier Peak deposit is located in the Cloudy Pass batholith (22 m.y.) near its west central contact with the Plummer Mountain migmatite gneiss. These gneissic country rocks formed during early Mesozoic metamorphism of Paleozoic (?) eugeosynclinal sedimentary and volcanic rocks. They are compositionally equivalent to a granodiorite and consist predominantly of quartz (25%), plagioclase feldspar (45%) and biotite (10%) with minor amounts of potassium feldspar and hornblende. Foliation in the gneiss strikes to the north-northwest, but several isoclinal folds are also present. The Cloudy Pass batholith intrudes the gneiss. The batholith is composed of three principal phases: 1) early border rocks of the Hart Lake complex (Cater, 1969); 2) main phases quartz diorite and granodiorite; and 3) late leucocratic rocks which include quartz diorite porphyry, granodiorite, quartz monzonite, and alaskite. The early border rocks are found only in the southern and eastern parts of the batholith and are not reported in the area of the Glacier Peak deposit. The main quartz diorite is composed of zoned plagioclase feldspar ( $AN_{35-50}$ , 50-65%), quartz, (15-20%), biotite (10%), hornblende (0-5%), and minor potassium feldspar (0-10%), according to Rose (1964). The quartz diorite is medium crystalline with subhedral plagioclase feldspar, hornblende, and biotite surrounded by large anhedral

crystals of quartz. This phase makes up 90 percent of the batholith in the area of the Glacier Peak deposit. Near the contact between the quartz diorite and the gneiss, the amount of potassium increases and leucocratic rocks are more abundant. Cross-cutting leucocratic porphyry dikes are closely associated with mineralization in the Miners Ridge area. Samples of plutonic rock from the Glacier Peak deposit (Table 21) contain much more  $K_2O$  and less  $CaO$  compared to samples of compositionally similar but unaltered plutons nearby (Tabor and Crowder, 1969; Cater, 1969). These differences are probably the result of hydrothermal alteration.

The Glacier Peak deposit is located at the intersection of overturned folds in the Plummer Mountain gneiss and east-west trending en-echelon shears which are a part of a north-northeast trending transverse structural belt (Grant, 1969; 1982). It consists of two spatially distinct "orebodies." The larger #1 orebody approximates the shape of an inverted cone, which grades at depths of 1000 feet below the surface into subeconomic values. To the northwest of the #1 orebody, three steeply dipping tabular bodies make up the #2 orebody. As mentioned above, the deposit occurs near the contact of the pluton with the gneiss at the intersection of overturned folds and northeast shears. Although breccia pipes are not directly associated with mineralization at Glacier Peak, two of these cylindrical intrusive masses crop out 2000 feet east-northeast of the #2 orebody (Grant, 1982), and elsewhere many other mineralized pipes are found in the Cloudy Pass batholith (Cater, 1969).

Table 21

Major oxide (weight percent) and trace element (ppm) data for samples from the Glacier Peak porphyry deposit.

Sample	GP-2	GP-3	GP-4	GP-5	GP-6	GP-7	GP-8	GP-9	GP-10	GP-11	GP-12	GP-13	GP-14	GP-15
Rock type	QM	QD	Monz	QD	latite	pppy	Aplite	Grd	Grd	Grd	Grd	QM	BX	Monz
Alt. type	prop.	pot?	phy	"fresh"	arg	"fresh"	"fresh"	arg	phy	pot	phy-pot	pot	phy	pot
SiO <sub>2</sub>	77.6	58.7	78.6											
TiO <sub>2</sub>	0.12	0.57	0.08											
Al <sub>2</sub> O <sub>3</sub>	12.0	16.0	9.8											
Fe <sub>2</sub> O <sub>3</sub>	0.39	3.30	0.56											
FeO	0.72	3.60	0.75											
MnO	0.02	0.17	0.03											
MgO	0.25	2.60	0.09											
CaO	0.95	3.20	0.26											
Na <sub>2</sub> O	2.10	3.00	0.39											
K <sub>2</sub> O	6.6	3.3	7.6											
TOTALS	100.75	94.44	98.16											
Ag	0.6	8.0	2.8	0.6	1.5	0.3	<0.3	5.0	4.7	5.5	11.9	0.3	5.0	13.8
Cu	850	9000	2010	720	1250	250	90	7500	7100	8700	16,200	400	5400	7600
Mo	3	5	60	1	1	2	2	3	6	6	280	20	690	17
Pb	20	90	8	11	100	7	10	30	16	12	20	10	60	100
Zn	60	820	110	55	110	15	40	255	225	235	460	35	310	230

Alt. types: prop = propylitic  
 phy = phyllic  
 pot = potassic  
 sil = silicified  
 arg = argillic

Mineralization of the #1 orebody consists of disseminated chalcopyrite, pyrite, pyrrhotite, and molybdenite with locally abundant scheelite, tennantite, and arsenopyrite. Minor amounts of sphalerite, galena and realgar have also been reported. Alteration and gangue minerals associated with sulfide mineralization include quartz, sericite, chlorite, carbonate (ankerite), orthoclase, tourmaline, and biotite. The highest grades of mineralization are associated with a potassic alteration assemblage, which contains abundant sericite, quartz, chlorite, and carbonate, in addition to biotite and potassium feldspar. Contacts between unaltered and altered host rocks are sharp. For example, the transition between altered mineralized and unaltered unmineralized host rocks may take place over distances of as little as 10 feet (Rose, 1964). Halos of pyrite and propylitic alteration are generally of small size and weak intensity at the Glacier Peak deposit. A somewhat unusual aspect of this deposit is the large plug of massive "bull" quartz, which is similar to that described at Ok Tedi in New Guinea (Bamford, 1972).

Rose (1964), in his study of the chemistry and mineralogy of the Glacier Peak deposit, noted that mineralized outcrops are defined by anomalously high concentrations of copper, molybdenum, potassium, and rubidium and lesser amounts of lead, zinc, gold, bismuth, and tungsten. These trends are supported by the more limited chemical data for major oxides and trace metals of the present study. In addition to large concentrations of most metals except lead (up to 16,200 ppm Cu, 690 ppm Mo, 820 ppm Zn, and 14 ppm Ag) that obviously

correlate with sulfide mineralization, a few samples exhibit depletions of calcium, sodium and strontium (Table 6 and 13). These undoubtedly accompanied potassium metasomatism during formation of biotite and potassium feldspar (at the expense of plagioclase feldspar) with potassic alteration.

Leaching of metals from surface outcrops of the #1 orebody has been reported by Rose (1964) and Grant (1982). Nonetheless, there has been little secondary enrichment of the deposit because of steep topography, abundant precipitation, and the resulting high rates of erosion. The surficial leaching of metals from surface samples in the Cascade Range should be considered when evaluating geochemical data from mineral prospects. The concentration of most metals in these samples will probably be lower than those in the unweathered equivalents at depth.

#### Margaret Porphyry Deposit

Unfortunately, information concerning the geology and character of mineralization at the Margaret deposit is largely confidential. This summary is based primarily on cursory descriptions by Grant (1969), Moen (1977), Hollister (1979), Ashley and Evarts (1980), and some data contained in exploration reports that were kindly provided by R. A. Metz of the Duval Corporation.

The Margaret porphyry copper prospect is in the northern part of the St. Helens mining district about 15 kilometers north-northeast of Mt. St. Helens in Skamania County, Washington. This deposit, also

known as the Earl or Ryan Lake, was discovered by Duval Corporation in 1970. However, this area had been prospected intermittently since 1891, when two farmers on a hunting trip found outcrops containing pyrite, chalcopyrite, arsenopyrite, galena, sphalerite, and tourmaline (Moen, 1977). Active prospecting in the 1890's and through the turn of the century uncovered only minor amounts of placer gold and small veins which were too low grade to warrant mining. Total recorded production from the Mt. St. Helens district is \$1587, most of which came from copper, gold, and silver extracted from the Sweden mine in the southern part of the district (Moen, 1977). In spite of the small past production, diamond drilling programs by Duval have indicated the presence of a copper deposit comparable in size to the Sierrita deposit (554 m.t. of 0.32% Cu and 0.033% Mo; Pennzoil Company, 1974, Annual Report) in southern Arizona (R. A. Metz, 1981, personal communication).

The Spirit Lake pluton, which is host to the Margaret deposit is a composite stock of Miocene age that intrudes tuffs, volcaniclastic rocks and flows of andesite and rhyolite of the Eocene Ohanapecosh Formation. According to Ashley and Evarts (1980), the various phases of the stock are, in order of emplacement seriate granodiorite, granodiorite porphyry, seriate quartz diorite, quartz monzonite, quartz monzonite porphyry, and granite porphyry. The seriate granodiorite (given the field name "quartz diorite" by Duval geologists and Hollister (1979)) is the host rock to the Margaret deposit. Modal analyses of the pluton by Hillman (1970) indicate that it

contains plagioclase (28-53%), orthoclase (8-10%), quartz (10-25%), and hornblende, biotite, pyroxene, magnetite, sphene, and apatite. The Spirit Lake pluton is similar in composition to the plutons of the Western Cascades in Oregon. Major oxide analyses of core samples from the Margaret property are presented in Table 22. Although these samples of the seriate granodiorite have been subjected to hydrothermal alteration, their analyses are comparable to that of a "fresh" sample of this phase obtained by R. P. Ashley of the U.S. Geological Survey (1981, written communication). K-Ar age determinations indicate that the Spirit Lake pluton is 21 m.y. old (Engels and others, 1976), whereas hydrothermal biotite from the Margaret deposit yields an age of 16 m.y. (Armstrong and others, 1976).

Open folds trending north to northwest have gently deformed the bedrock in this part of the Washington Cascades, and dips rarely exceed 30° (Moen, 1977). Grant (1969) has suggested that a "transverse structural belt," a system of east-west en-echelon shears may cut through the district. Hollister (1979) has reported a roughly circular set of mineralized fractures around the deposit. Some of the mineralized structures are brecciated and contain tourmaline in addition to quartz and sulfides.

Mineralization at the Margaret deposit consists chiefly of pyrite and chalcopyrite that are present in veinlets and as very fine-grained disseminations. Alteration and mineralization are predominantly fracture controlled. Alteration selvages in wall rock adjacent to veins and veinlets create an overall zonation in the deposit

Table 22

Major oxide (weight percent) and trace element (ppm)  
data for samples of granodiorite and breccia  
from Margaret porphyry prospect

Sample Rock type Alteration Type	MM-1 GD prop	MM-2 GD phy	MM-3 GD pot	MM-4 GD phy	MM-5 GD phy	MM-6 GD phy	MM-7 GD phy	MM-8 BX phy
SiO <sub>2</sub>	63.2	63.2	63.8	63.1				
TiO <sub>2</sub>	0.71	0.85	0.86	1.10				
Al <sub>2</sub> O <sub>3</sub>	15.5	15.7	15.1	17.4				
Fe <sub>2</sub> O <sub>3</sub>	3.90	2.30	1.60	0.93				
FeO	3.40	1.30	1.90	2.50				
MnO	0.03	0.02	0.02	0.02				
MgO	1.90	1.40	1.70	3.60				
CaO	3.40	3.00	3.70	3.90				
Na <sub>2</sub> O	2.60	2.80	3.20	3.10				
K <sub>2</sub> O	<u>2.5</u>	<u>1.9</u>	<u>1.8</u>	<u>1.5</u>				
TOTAL	97.14	92.47	93.68	97.15				
Ag	0.4	1.1	0.9	0.5	0.5	0.9	0.6	0.5
Cu	850	11,400	7500	1190	380	5100	2150	900
Mo	6	45	780	5	4	35	6	16
Pb	12	8	9	10	8	9	8	8
Zn	35	30	25	25	40	35	100	13

from a central potassic core outward to phyllic and propylitic assemblages. However, alteration and metallization are not pervasive and large blocks of "fresh" rock may be surrounded by mineralization (R. A. Metz, 1981, personal communication). Sulfide assemblages are dominated by chalcopyrite and pyrite with variable minor to trace amounts of bornite and molybdenite. Associated gangue minerals include quartz, carbonate, chlorite, and sometimes tourmaline. The sulfides have undergone only superficial oxidation. Zones of oxidation and leaching reach a maximum thickness of 300 feet on hill tops. Thus the deposit does not have any substantial blanket of secondary enrichment. Included in Table 22 are analyses for the trace elements copper, molybdenum, lead, zinc, and silver. Copper and molybdenum values are obviously anomalous for rocks of these compositions. In contrast, the values for lead, zinc, and silver are largely indistinguishable from background values. As is normally the case, samples of propylitized rock are not as strongly mineralized as are those which have undergone phyllic and potassic alteration. Major oxide analyses obtained for four samples of granodiorite from drill core do not record any significant changes that are readily correlative with intensities of hydrothermal alteration or metallization.

Breccia pipes are not known in the Margaret deposit (R. A. Metz, 1981, personal communication), although to the north of the deposit, Hollister (1979) reports a large brecciated area which is cemented by tourmaline, quartz, and sulfides. Ashley and Evarts (1980) also report widespread argillization and silicification of bedrock to the

north, possibly indicating the presence of another hydrothermal center in that area.