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Title: GEOLOGY AND MINERALIZATION OF THE SOUTHERN SILVER STAR STOCK, WASHOUGAL MINING DISTRICT, SKAMANIA COUNTY, WASHINGTON

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Abstract approved: ______________________

Cyrus W. Field

The Washougal Mining District is located on the western flanks of the southern Cascade Range of Washington, approximately 50 km (30 miles) northeast of Vancouver, Washington. The district has produced only $573 since 1903, derived from copper and silver. The presence of hydrothermal mineralization and breccia pipes similar to those associated with many porphyry copper type deposits elsewhere signifies an above average exploration potential for parts of the district.

Bedrock in the southern part of the district consists of northwesterly dipping basalt and andesite flows, and volcaniclastic breccias of the East Fork (Ohanapecosh) Formation. Flat-lying basalt and basaltic andesite flows of the Skamania Formation unconformably overlie the East Fork units. These two formations range in age from late Eocene to early Miocene.

The East Fork and basal members of the Skamania Formation are intruded by the Silver Star stock, which is of probable middle Oligocene to early Miocene age. This composite intrusion is comprised of small outlying plugs of intrusive andesite and diorite, and a larger mass containing quartz diorite, granodiorite, vesicular porphyritic quartz diorite, and granitic aplite, in probable order of emplacement. Chemical trends indicate differentiation from a single magma. An alkali-lime index of 60.8 percent indicates that the rock suite is representative of a highly calcic calc-alkaline magmatic sequence.

Hydrothermal alteration associated with the Silver Star stock is analogous to that described for porphyry copper deposits, with the exception that the potassic and argillic assemblages are not present. Propylitic alteration affects most of the stock and forms a contact aureole in the adjacent volcanic country rocks. Minerals of the phyllic alteration assemblage are closely associated with shear zones, quartz veins, and breccia pipes.

Albite-epidote hornfels metamorphism is recognized in one locality on the southeast margin of the Silver Star stock.

Metallization in the southern Washougal District occurs as narrow quartz-sulfide veins within both the stock and the adjacent volcanic rocks. The veins generally trend northwest and have nearly vertical dips. Near the intrusive contact, sulfides of copper predominate over those of lead and zinc.

The quartz veins are inferred to be the channelways for ascending hydrothermal fluids that formed the breccia pipes of the district.

Geology and Mineralization of the Southern Silver Star Stock, Washougal Mining District, Skamania County, Washington

by

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THE GEOLOGY AND MINERALIZATION OF THE SOUTHERN SILVER STAR STOCK, WASHOUGAL MINING DISTRICT, SKAMANIA COUNTY, WASHINGTON

INTRODUCTION

The Washougal Mining District is located in southwestern Washington on the western slopes of the Cascade Range, approximately 50 km northeast of Vancouver, Washington. Mineral deposits of this district are generally small in size and production, with limited surface exposure. Principal metals produced in its 75 year history were copper, lead, zinc, and minor amounts of gold and silver. Interest in the area has been renewed in recent years as old mining districts are re-evaluated in terms of new metallogenetic concepts and new exploration techniques.

Location, Access, and Topography

The Washougal Mining District comprises an area of about 427 square km in eastern Clark County and southwestern Skamania County (Fig. 1). The district is in the southern part of the Cascade Mountain physiographic province, a region which consists of a volcanic plateau that is being dissected by numerous streams (Moen, 1977). The area of study occupies approximately 55 square km in the south-central part of the mining district. Roughly one-half of the area lies in the Gifford Pinchot National Forest, and the remaining southern portion

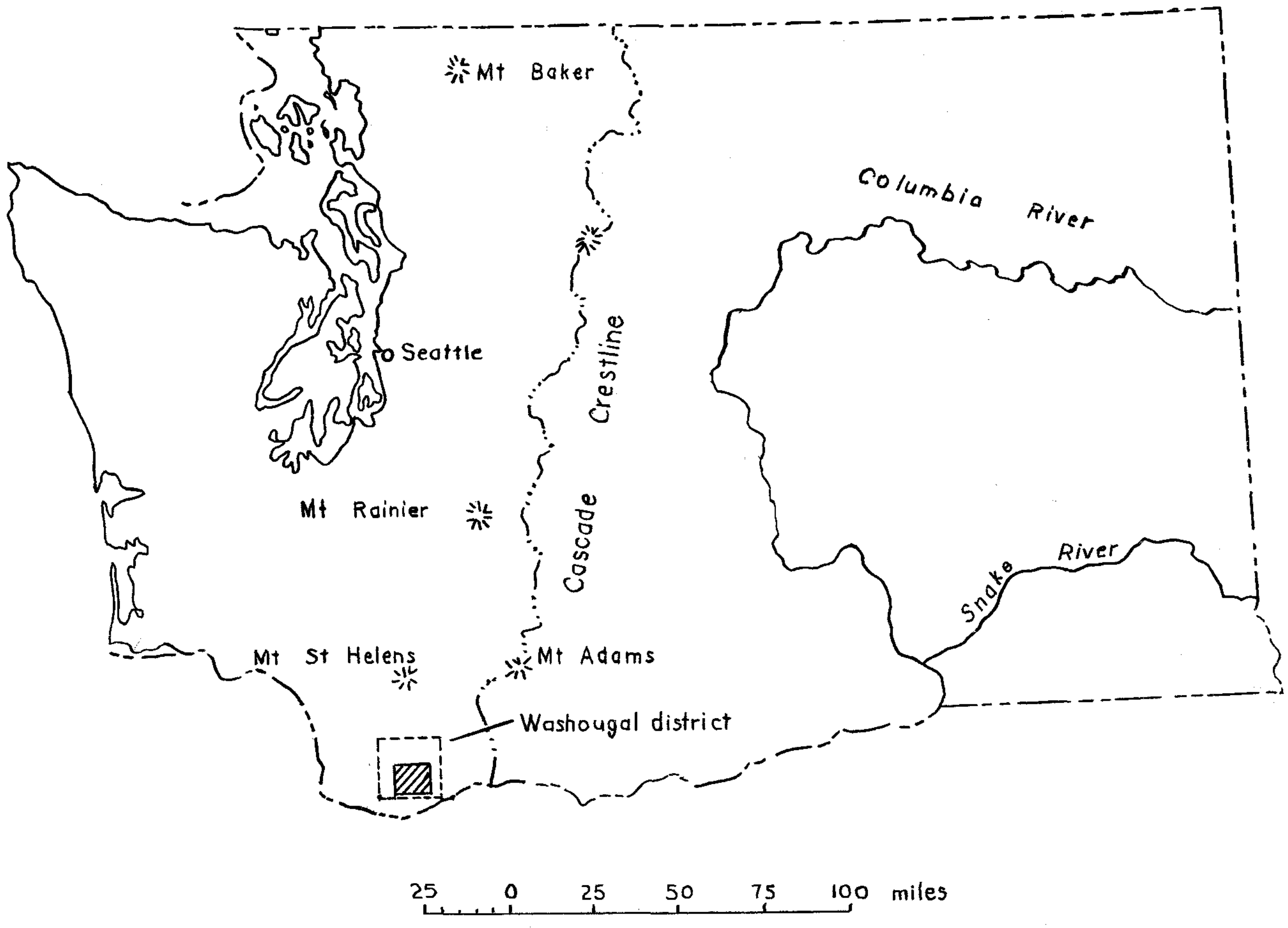

Figure 1. Index map of Washington showing the location of the study area (shaded)

is on Washington State Forest land.

The thesis area is accessible from the south via Washougal River Road (State Highway 8B), and a series of gravel roads maintained by the state. Abandoned logging roads and Forest service roads allow access to one-half the area, the remainder being inaccessible except by foot.

Topographic relief is approximately 942 m, ranging from an altitude of 396 m at the headwaters of Wildboy Creek, to 1338 m at the top of Silver Star Mountain. Because of extensive forest fires between 1902 and 1936, much of the Washougal District is devoid of heavy stands of timber, and is generally covered by second generation evergreen and thick deciduous brush. Vegetation is thin above an altitude of approximately 914 m, and rocky talus slopes predominate on the hillsides.

Previous Investigations

Allen (1932) examined the general geology of the region in his unpublished thesis pertaining to the lower Columbia River Gorge, and he was the first to describe the large granodiorite stock of the Washougal District, which he named the Silver Star Formation. Felts (1939a) investigated the petrology of the Silver Star Stock and the surrounding volcanic rocks. Fiske and others (1963) established the volcanic stratigraphic nomenclature of the southern Cascades in their detailed examination of the geology of Mt. Rainier National Park. In addition, Wise (1970) has also detailed the Cenozoic history of volcanism in the Wind River area, east of the Washougal District. Regional correlations of the volcanic units in the southern Cascades have been undertaken by Hammond (1974), Hammond and others (1975, 1977).

The mineral deposits associated with the Silver Star Stock were first considered by Heath (1966) in a thesis that was largely devoted to a microscopic examination of the ores. Grant (1969) summarized the literature of the district in his report concerning mineralization in the Washington Cascades. Recently, Moen (1977) has described the general geology and mineral deposits of the Washougal and nearby St. Helens Mining Districts. Finally, Schriener (1979) examined the geology and mineralization of the northern part of the Washougal Mining District.

Purpose and Methods

The primary objective of this investigation was to prepare an accurate geological map of the south-central part of the Washougal Mining District. Special attention has been given to defining the separate phases within the Silver Star Stock, and some effort was directed toward clarifying the stratigraphy of the associated volcanic and volcaniclastic rock units. The effects of hydrothermal alteration in metallized areas, and the development of breccia pipes have been considered in this study.

Field work was conducted in the Spring and late Fall of 1978, using an enlarged portion (1:24, 000) of the Bridal Veil and Lookout Mountain quadrangles for a base map. Attitudes of joints and rock units were taken with a Brunton compass directly from outcrops, where possible. Rock samples were collected for petrographic, chemical, and trace element analyses, and samples of stream sediment were collected for trace element analyses.

Petrographic examinations of approximately 32 thin sections were performed to identify the minerals and their textural relationships within the more important rock units, using a Leitz student model monocular petrographic microscope. Composition of plagioclase feldspars were determined using the Michel-Levy or combined Carlsbad-Albite methods described by Kerr (1959). Modal analyses were obtained for selected samples using a Leitz mechanical stage and point counter.

Trace element chemical analyses for Cu, Mo, Pb, Zn, and Ag were performed by contract with Chemical and Mineralogical Services, Salt Lake City, Utah. Major oxide chemical analyses were conducted by contract with Skyline Laboratories, Wheatridge, Colorado.

REGIONAL GEOLOGIC SETTING

The Cascade Range of the Pacific Northwest extends north-south for over 1000 km and averages 90 km in width. Volcanism has been characteristic of the region, beginning about 50 million years ago, and continuing, possibly episodically, to the present time (Vance and Naeser, 1977; McBirney and others, 1974). The range is characterized by a number of glaciated volcanoes, from Mt. Garibaldi in southwest British Columbia to Lassen Peak in northern California. These volcanoes overlie deeply eroded, warped, and altered Tertiary volcanic and volcaniclastic strata, and a variety of pre-Tertiary rocks. The Tertiary volcanic rocks, which occur principally in a central segment about 750 km long, form the bulk of the range.

The southern Cascade Range of Washington is composed predominantly of Tertiary volcanics, but also includes representatives of all rock types underlying the range. These rocks are grouped into pre-Tertiary units, Western Cascade volcanic and sedimentary strata, lavas of the Columbia River Basalt Group, and late Cenozoic volcanic rocks of the High Cascades (Hammond and others, 1977).

The Tertiary volcanic strata are informally designated the Western Cascade group by Hammond and others (1977). A sequence of ash-flow tuffs, called the Stevens Ridge Formation, form the widespread stratigraphic marker separating the Western Cascade group into upper and lower parts (Table 1). This distinctive formation is composed of light-colored interstratified dacitic to rhyodacitic ash-flow tuffs, laharic breccias, volcaniclastics, and a few porphyritic lava flows (Fiske and others, 1963; Waters, 1961; Hammond, 1974; Harle, 1974; Hammond and others, 1976, 1977). It has been dated as middle Oligocene to early Miocene by Vance and Naeser (1977).

Stratigraphically above the Stevens Ridge Formation is the Fifes Peak Formation (Fiske and others, 1963). It also is included in the upper section of the Western Cascade group. This formation contains a complex of overlapping and possibly interfingering sequences of pyroxene andesite lava flows, and minor laharic breccias and pyroclastic flows. According to Schriener (1979), Hammond has recently delineated at least seven members of the Fifes Peak Formation, in order to develop a lithologically coherent formation.

The Eagle Creek Formation unconformably overlies the Fifes Peak Formation, and is included in the High Cascade Group, as classified by Hammond and others (1977). It has been defined as a sequence of volcanic conglomerates, sandstones, and tuffs, and has been assigned an early Miocene age on the basis of fossil flora examinations (Chaney, 1918, 1920, 1959; Wise, 1970).

Within the lower part of the Western Cascade group, and lying unconformably below the Stevens Ridge Formation, is the extensive

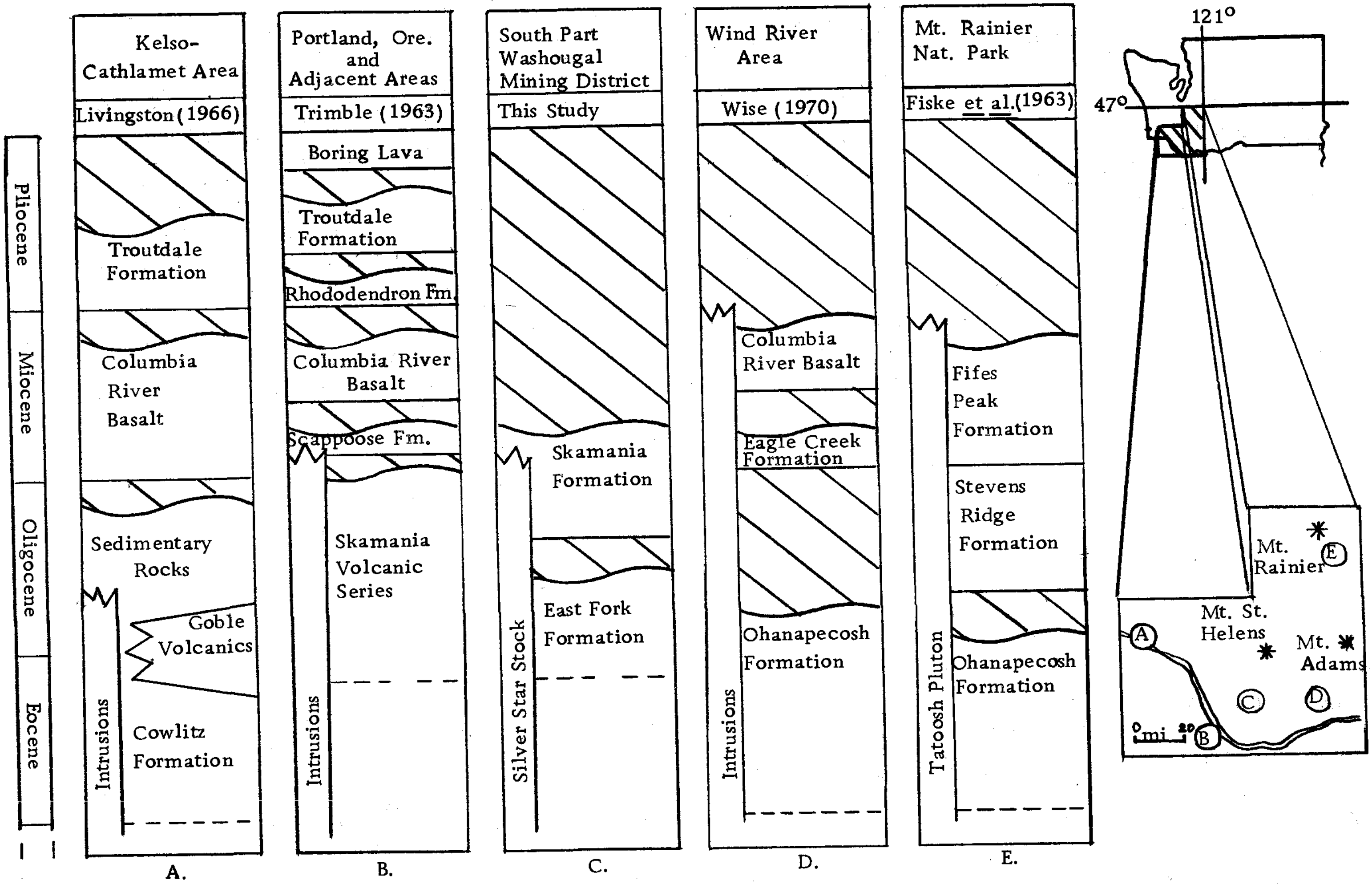

Table 1. Stratigraphic nomenclature in the southern Washington Cascades

Ohanapecosh Formation. This unit, first described at Mt. Rainier National Park, is middle Eocene to late Oligocene in age (Fiske and others, 1963; Vance and Naeser, 1977). The formation consists of interstratified lava flows of basalt and andesite, laharic breccias, tuffs, and volcaniclastic rocks of andesitic to rhyodacitic composition. It is interpreted to have been deposited in both subaqueous and subaerial environments, according to Fiske (1963). The Ohanapecosh Formation has been mapped as far south as the Columbia River (Hammond and others, 1976, 1977; Wise, 1970). Across the river, to the south, the Ohanapecosh Formation has been tentatively correlated with the Little Butte Volcanics (Peck and others, 1964) by Hammond, according to Schriener (1979). In addition, Wise (1970) has suggested that the Ohanapecosh Formation could interfinger with marine Eocene units, such as the Cowlitz Formation to the west (Wilkinson and others, 1945; Livingston, 1966).

The Cowlitz Formation is a basinal sedimentary unit consisting of massive to thin bedded arkosic sandstone, siltstone, and shale, and with minor amounts of conglomerate, gritstone, and volcanic sandstone. The formation is at least 550 m thick, and tends to become more coarse grained to the east. The Cowlitz Formation is considered to be Eocene in age, on the basis of fossil flora examinations (Livingston, 1966).

Conformably overlying and interfingering with the Cowlitz

Formation is the Goble Volcanics, of Eocene to Oligocene age. This unit is composed of a series of basaltic flows, flow breccias, pyroclastic material, and scattered intercalated sedimentary beds (Wilkinson and others, 1946; Livingston, 1966). The Goble Volcanics are at least 300 m thick west of the Washougal District.

Most of the rocks of the Western Cascade group are extensively altered, and have been subjected to zeolite grade metamorphism (Fiske and others, 1963; Race, 1969; Wise, 1970; Fischer, 1971; Hartman, 1973). In addition, many zones of hydrothermal alteration, consisting mostly of silicification and argillization, are associated with epizonal plutons (Grant, 1969; Hartman, 1973).

The epizonal plutons of the Washington Cascades range in size from small plugs and stocks to batholiths, and in composition from diorite to granite. Also, many dikes and plugs of andesite and basalt intrude the Tertiary strata. Radiometric age determinations for the intrusions are limited in number, but most vary from 13 to 40 million years in age (Laursen and Hammond, 1974; Engels and others, 1976; Armstrong and others, 1976).

Stratified sedimentary and volcanic sequences that comprise the western flank of the Cascade Range in southern Washington are moderately deformed by a series of broad northwest-trending, en echelon, doubly plunging folds (Zeitz and others, 1971). In contrast, folds east of the crest of the Cascade Range are characterized by east to northeast trends. The boundary between the eastern and western trends of folds is covered by High Cascade Group volcanic rocks. Major faults in the range are oriented predominantly northwest, and are characterized by both right-lateral slip and normal displacements. Most occur near the Columbia Plateau, where they cut rocks of the Columbia River Basalt Group. A northwest trending fault zone along the Wind River separates opposite fold trends, and is the locus of several centers of volcanic and thermal spring activity (Hammond and others, 1976).

VOLCANIC AND VOLCANICLASTIC ROCKS

The volcanic and volcaniclastic bedrock of the southern part of the Washougal Mining District consists of basaltic to andesitic flow units, coarse epiclastic breccia, and minor volumes of bedded tuffs. These strata correspond to the lower part of the Western Cascade Group of Hammond and others (1977). They have been termed the Skamania Andesite Series by Felts (1939a), and the Skamania Volcanic Series by Trimble (1963). Schriener (1979) informally divided the Skamania rocks into two formations, the Skamania formation and the underlying East Fork formation, separated by an angular unconformity (Plate 1).

East Fork Formation

The oldest strata in the area of study is the East Fork formation, as informally designated by Schriener (1979). It predominates the bedrock in the southeast portion of the area. It is composed of intercalated epiclastic tuff breccia, slightly smaller volumes of flow basalts and basaltic andesites, and a few small, discontinuous lenses of water-laid tuff. The flow units will generally form resistant bluffs, while the volcaniclastics tend to form moderately steep, vegetated hillsides. The present thickness of the formation is approximately 550 meters. It dips 20 to 25 degrees in a northwesterly direction, although one attitude of 43 degrees was recorded. Best exposures of the strata are found in sec. 27, T. 3 N., R. 5 E.

Character and Lithology - Volcaniclastics

The volcaniclastic rocks of the East Fork formation, based on the classification of Fisher (1961), are entirely epiclastic in nature. They total an estimated 65 percent of the formation within the study area. As these rocks do not normally form outcrops, the best exposures are usually along roadcuts. Two types of epiclastic volcanic rocks may be seen in such exposures; tuff breccias and a few minor interbeds of water-laid tuff.

The tuff breccias are the most abundant of the rock types that comprise the East Fork formation. Thicknesses of the beds may vary from approximately one meter to greater than 12 meters. However, the lateral continuity of individual beds could not be estimated accurately because of inadequate exposures. Sorting and bedding were not observed in any tuff breccia outcrops.

Samples of the tuff breccia on weathered surfaces are usually light olive gray (5Y 6/1) in color, with some surfaces covered by black pyrolousite (?) dendrites. Fresh specimens appear pale olive (10Y 6/2) in color. Clasts are heterolithologic, and vary from ash-sized particles up to fragments 5 cm in average diameter. Clasts larger than two mm in average diameter constitute an estimated

45 percent of the rock. The larger clasts are generally more rounded. The East Fork formation is only moderately indurated and tends to break within the matrix around clasts, rather than through the clasts.

The matrix of the tuff breccias in thin section exhibits a substantial degree of alteration, with epidote, quartz, chlorite, and unidentified clays as the major alteration products. Clasts are angular to subrounded in shape, and show alteration equivalent to that of the matrix. These clasts consist predominantly of finely crystalline basalt and basaltic andesite, commonly with pilotaxitic textures. Others include broken individual grains of plagioclase and pyroxene.

The small discontinuous lenses of water-laid tuff of the East Fork formation weather to a yellowish gray (5Y 7/2) and are medium gray (N5) on fresh surfaces. These rocks tend to break along thin bedding planes, varying from one to ten mm in thickness. Iron stains and pyrolousite (?) dendrites are common along the well-developed joint surfaces. Clasts vary from ash-sized to approximately one mm in diameter, and excellent sorting and graded bedding are ubiquitous. Sedimentary current structures such as cross-bedding, flute casts, etc., are not evident. In accordance with the classification of Fisher (1961), these rocks are termed epiclastic volcanic siltstones.

Petrographic examination reveals that the water-laid tuffs have been altered significantly, especially along the coarsest bedding planes. Alteration minerals are epidote, chlorite, quartz, and unidentified clays. The clay commonly forms small (less than 0.1 mm in diameter) spherical masses visible only in thin section. This orbicular texture also appears in some nearby but dissimilar rock units. The well-sorted clasts consist of angular to subangular grains of plagioclase, clinopyroxene, pilotaxitic basalt fragments, and amorphous lithic fragments. Glass and pumice shards, if ever present, have been altered beyond recognition.

Character and Lithology - Mafic Flows

Approximately 35 percent of the East Fork formation is composed of flows of porphyritic basalt and basaltic andesite, which form many prominent bluffs in the area. The best exposures of the flows may be found in sec. 27, T. 3 N., R. 5 E. Thicknesses of individual flows varies from one to as much as twenty meters. These outcrops are well-jointed, although no columnar features are observed. Lateral extent of the flows is inferred to be as much as one kilometer.

Specimens of the mafic flows exhibit a brownish gray (5YR 4/1) color on weathered surfaces, and are medium gray (N5) on fresh surfaces. Megascopically visible phenocrysts consist of plagioclase feldspar and pyroxene, and constitute approximately 30 percent of the rock. The average length of the plagioclase feldspar phenocrysts is three mm, whereas that of the pyroxenes is two mm. Some appear to exhibit a glomeroporphyritic texture. Preferred orientations to the phenocrysts were not noticeable in any of the samples collected. Alteration has produced epidote in the cores of plagioclase crystals, and chlorite has replaced pyroxenes.

Petrographic examination reveals corroded, and often zoned phenocrysts of plagioclase feldspar in an intersertal groundmass. The crystals are normally zoned as the cores have the more calcic composition. Carlsbad twins are commonly observed in the large phenocrysts, and Pericline twinning is very rarely present. Cores of the larger phenocrysts are compositionally An_{64-66}, as determined by the combined Carlsbad-Albite method described by Kerr (1959). Smaller crystals of plagioclase feldspar in the groundmass have a composition range of An_{40-50} as determined by the Michel-Levy method. Rare crosscutting alteration veinlets, always less than one mm wide, contain radiating fibrous actinolite, anhedral epidote, chlorite, and scattered grains of magnetite.

The phenocrysts of pyroxene include both clinopyroxene and rarely orthopyroxene. They are subhedral to euhedral in shape, and average about one mm in cross section, and up to three mm in length. Where altered, they may be replaced by chlorite, magnetite, and uncommonly by fringes of actinolite. A few large phenocrysts of clinopyroxene were found to contain poikilitic inclusions of plagioclase feldspar and apatite. Pyroxene phenocrysts are usually twinned. Hornblende was not detected in any of the thin sections examined.

Phenocrysts of primary magnetite show subhedral outlines, and what appears to be a resorbed texture. Holmes (1928, p. 198) suggests that such textures may indicate immature crystals, rather than later re-equilibration. The magnetite grains average one mm in diameter.

Scattered crystals of apatite are subhedral to anhedral, less than 0.25 mm in size, and are most obvious when enclosed by phenocrysts of plagioclase.

Chemistry

Trace element analyses were performed for Ag, Cu, Mo, Pb, and Zn upon one volcaniclastic specimen, and trace element plus major oxide analyses were performed upon one mafic flow specimen of the East Fork formation. These, plus four modal analyses are listed in Table 2. Though analyses of so few samples cannot be considered statistically meaningful, they at least yield some indication of the concentrations of the various elements and oxides. The analysis of the mafic flow specimen is plotted on the chemical classification chart of MacKenzie and Chappell (1972) in Figure 2. Also listed are the major oxide compositions of an average calc-alkaline andesite

Table 2. Modal mineral, trace element, and major oxide analyses for rocks of the East Fork formation.

Minerals (percent)	S78-22[1] (volcaniclastic)		S78-30[2] (mafic flow)
Clasts		Plagioclase	31
basalt, andesite	26	Cpx (augite)	4
plagioclase	7	Opaques	2
pyroxene	4	Accessory min.[5]	1
dacite	1	Alt. plag.[6]	8
alteration clots[3]	7	Groundmass[7]	54
Groundmass[4]	55		100
	100		

Major Oxides (percent)	S78-30	Calc-alk. andesite[8]	Hawaii tholeiite[9]	Oceanic tholeiite[10]
SiO_2	54.3	58.65	49.4	49.34
TiO_2	1.3	0.79	2.5	1.49
Al_2O_3	16.8	17.43	13.9	17.04
Fe_2O_3	2.1	3.21	3.0	1.99
FeO	5.5	3.48	8.5	6.82
MnO	0.14	0.10	0.2	0.17
MgO	3.9	3.28	8.4	7.19
CaO	8.1	6.26	10.3	11.72
Na_2O	3.0	3.82	2.1	2.73
K_2O	0.66	1.99	0.4	0.16
H_2O^+	1.4	1.06	--	0.69
	97.2	100.07	98.5	99.34

Trace Elements (ppm)	S78-22	S78-30	Threshold Pac. NW[11]	(-) less than
Ag	0.6	0.4	-0.1	
Cu	100	120	50	
Mo	1	1	-1	
Pb	12	10	20	
Zn	60	50	60	

[1] NW 1/4 sec. 35, T. 3 N., R. 5 E.; [2] NW 1/4 sec. 27, T. 3 N., R. 5 E.; [3] clays, chlorite, quartz, zeolites; [4] Alt. glass, cpx and plag. microlites; [5] Apatite, sphene; [6] chlorite, epidote, carbonate; [7] Crystal frags. less than 0.25 mm dia., clays; [8] McBirney, 1969, p. 503; [9] MacDonald and Abbott, 1970, p. 113; [10] Engel and others, 1965, p. 721; Field and others, 1974, p. 17.

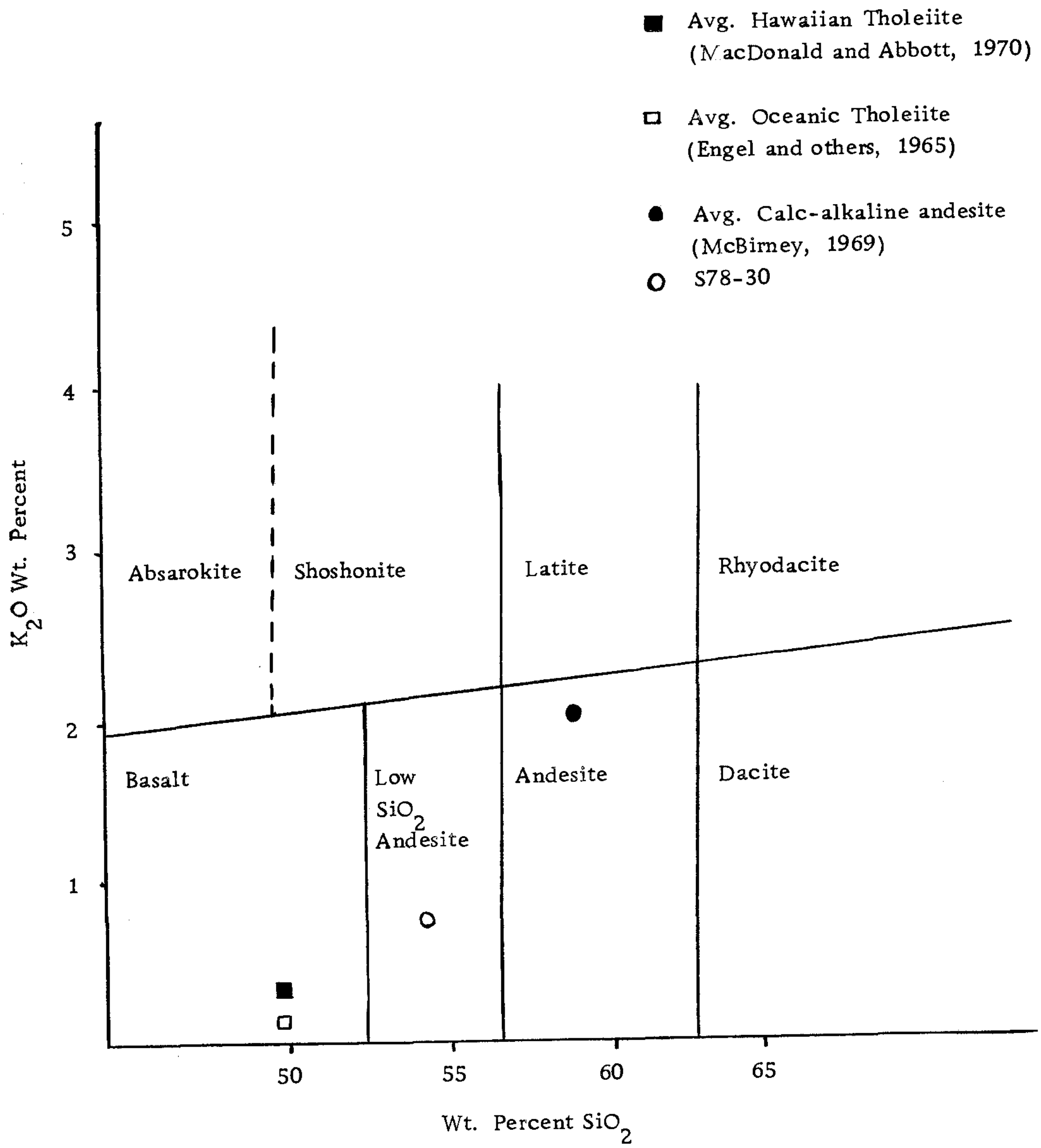

Figure 2. Chemical classification of an East Fork formation flow rock (After MacKenzie and Chappell, 1972)

(McBirney, 1969), an average tholeiitic basalt from Hawaii (MacDonald and Abbott, 1970), and an average oceanic tholeiite (Engels and others, 1965).

The major oxide analysis of sample S78-30 falls approximately between the calc-alkaline andesite of McBirney (1969), and the tholeiitic basalts of MacDonald and Abbott (1970), and Engel, Engel, and Havens (1965). Thus it is a "low-SiO_2" andesite as indicated on the diagram of MacKenzie and Chappell (1972) (Fig. 2). Although an average chemical analysis is not offered, the analysis of the sample from the East Fork formation correlates well with the "basaltic andesites" of Coates (1968).

Origin

The tuff breccias of the East Fork formation are interpreted to be subaqueous volcanic mudflows, in accordance with the criteria established by Fisher (1960) and Fiske (1963). Specifically, these breccias exhibit a heterogeneous composition and lack of sorting; the fragments are usually broken and in various stages of alteration; the matrix lacks vesicular and pumiceous material; and the larger clasts tend to be more rounded than the smaller ones. The thin, well-sorted water-lain tuff units were deposited in relatively quiet, subaqueous conditions, at some depth below wave base, or sheltered from disrupting currents (Pettijohn, 1975). The smaller fragments could have been deposited by ash falls that rained into the water, or may be the finer particles of a submarine mud flow that were held in suspension for a longer period of time. The intercalated mafic flows are interpreted to have been deposited subaerially, because of the lack of pillow structures and textures suggestive of subaqueous autobrecciation. Thus, the bulk of the East Fork formation was deposited in an aqueous environment, in which volcanic eruptive centers were periodically emergent as islands.

Correlation and Age

The series of "vitric Tuffs" on the southeast margin of the Silver Star stock, in the upper headwaters of Dougan Creek, have been assigned to the Eagle Creek Formation (Chaney, 1918, 1920) by Felts (1939a). Since that time, however, the Eagle Creek Formation has be been re-defined by Wise (1970) as a series of volcanic conglomerates, sandstones, and tuffs, which unconformably overlie the Ohanapeçosh Formation of Fiske, Hopson, and Waters (1963).

On that basis, therefore, it is suggested that the Eagle Creek Formation does not crop out within the area of study, contrary to Felts (1939a). The poorly sorted paraconglomerates which compose the bulk of the Eagle Creek rocks have a white to buff matrix that weathers to dark red, and contain abundant fragments of pumice. They are interpreted by Wise (1970) to have been deposited as laharic mud flows. The breccias of the East Fork formation, on the other hand, have an altered, greenish, clay-rich matrix, and contain little or no pumiceous material. Consequently, they fit the description of subaqueous mud flows given by Fisher (1960) and Fiske (1963). In addition, the East Fork formation contains a large volume of intercalated mafic flows, whereas Wise (1970) describes only two small flow units within the Eagle Creek Formation.

Structural attitudes are also different between the two formations. The Eagle Creek Formation is roughly horizontal, and is concordant to the overlying Yakima Basalts (Wise, 1970). In contrast, the East Fork units dip to the northwest over a broad area. Finally, an unconformity such as described by Wise (1970) was not found in a traverse along the length of Dougan Creek. If the Eagle Creek Formation is present in the district its contact with the underlying Ohanapecosh Formation should have been evident.

With reference to lithology, regional geology, and stratigraphic position, it appears that the East Fork Formation southeast of the Silver Star Stock correlates with the Ohanapecosh Formation of Fiske, Hopson, and Waters (1963), Wise (1970), and Hammond and others (1977). Outcrops of this formation have been reported in several locations near the Washougal Mining District. On the northern boundary of Skamania County, in the Camp Creek mining area, strata of the Ohanapecosh Formation have been intruded by a Tertiary quartz diorite stock (Simon, 1972). To the southeast, in the Columbia River Gorge, Wise (1970) reports exposures of the Ohanapecosh Formation, as does Hammond and others (1977). Hammond also has described outcrops of probable Ohanapecosh rocks on the outskirts of Camas, Washington. These outcrops were included in the Skamania Volcanic Series by Felts (1939b) and Trimble (1963). According to Schriener (1979), Hammond considers the Goble Volcanics (Wilkinson and others, 1946; Livingston, 1966) west of the Washougal District to be a local eruptive center within the Ohanapecosh Formation.

The East Fork Formation is interpreted to be late Eocene to middle Oligocene in age. Trimble (1963) examined fossil flora from the lower Skamania Volcanic Series, and assigned them to the late Eocene epoch. Wise (1970) collected flora from the Ohanapecosh Formation in the Wind River area, and reported them to be Oligocene in age. Vance and Naeser (1977) used fission track methods on zircons of the Ohanapecosh Formation, and arrived at a middle Oligocene date. Finally, the Goble Volcanics west of the Washougal district are considered to be late Eocene to early Oligocene in age on the basis of fossil flora assemblages (Wilkinson and others, 1946; Livingston, 1966).

Skamania Formation

The East Fork Formation is overlain by the relatively undeformed and flat-lying Skamania formation. This designation is also informal, and follows the nomenclature established by Schriener (1979). The actual contact between the two formations is obscured by talus and vegetation, but is inferred to be an angular unconformity, because of the significant differences between their respective attitudes.

The Skamania formation is largely composed of porphyritic volcanic flow units, with minor interbeds of lapilli tuff. The best exposures of this formation are found in the northern half of sec. 18, and southern half of sec. 7, T. 3 N., R. 5 E. Outcrops of the lapilli tuff are practically non-existent, except on the steep southeastern face of Silver Star Mountain.

Character and Lithology - Mafic Flows

The mafic flows of the Skamania formation tend to form steep, resistant bluffs. The flows comprise approximately 95 percent of the entire formation. Jointing is common, and excellent columnar joints were observed in a large bluff 0.5 km west of Silver Star Mountain. Thicknesses of the individual flows may vary from 5 to as much as 25 m.

Hand specimens of the mafic flows vary in color from medium gray (N5) on weathered surfaces, to dark gray (N3) on fresh surfaces. Visible phenocrysts of plagioclase feldspar and pyroxene amount to approximately 20 percent of the rock. Some flows appear to be slightly vesicular, and the vesicles have become partially filled by zeolite minerals and quartz.

The flow rocks of the Skamania formation exhibit diabasic to intergranular textures in thin section. The larger phenocrysts of plagioclase are up to two millimeters in length. They commonly display altered rims or cores. Normal zoning is common to these phenocrysts, and twinning is exclusively polysynthetic. Compositions of the plagioclase average An_{50}, but one specimen from a flow 0.3 km north of Silver Star Mountain yielded plagioclase feldspars having a composition of An_{64}. All determinations were made using the Michel-Levy method, as described by Kerr (1959). Phenocrysts of clinopyroxene are usually twinned, and average two millimeters in cross-section. Only one phenocrysts of orthopyroxene was found in the four thin sections examined.

The groundmass of these flow rocks in the Skamania formation is commonly pilotaxitic, and is composed of unoriented laths of plagioclase feldspar, interstitial clinopyroxene, magnetite, and unidentified clay minerals, probably derived from the alteration of glass. Vesicles are usually less than one millimeter in diameter, and may be filled with chlorite, quartz, and radiating fibrous zeolite. Modal analyses of two specimens are listed in Table 4.

Character and Lithology - Volcaniclastics

Volcaniclastic sedimentary rocks of the Skamania formation are poorly resistant to weathering, and consequently do not form outcrops. They constitute an estimated five percent of the volume of the formation. Best exposures of these rocks may be found in the northern half of sec. 18, T. 3 N., R. 5 E., on the steep cliffs on the southeast side of Silver Star Mountain.

One specimen of lapilli tuff was collected near Silver Star Mountain. Its color is olive gray (5Y 4/1) on exposed surfaces and dark greenish gray (5G 4/1) on fresh surfaces. The fragments average three millimeters in diameter, and are angular to subrounded and poorly sorted. Stratification was not observed either in hand specimen or in outcrops. Megascopically visible fragments include basalt, pumice, feldspar, and lithic grains. The matrix is composed of fine ash, altered feldspar fragments, and glass shards (?). Mafic minerals were not found either as fragments or within the matrix.

Chemistry

Two trace element analyses were performed upon a single mafic flow specimen from the Skamania formation (Table 3). That is, separate chips from the same hand sample were analyzed. In general, the average of the two analyses in each of the trace elements

Table 3. Modal mineral, trace element, and major oxide analyses for rocks of the Skamania formation.

Minerals (percent)	S78-73a[1]	S78-74[2]
Phenocrysts		
plagioclase	59	34
Cpx (augite)	15	tr
opaques	tr	1
Groundmass		
plagioclase	--	35
Cpx (augite)	--	20
Alt. glass	15	9
accessory mins.[3]	tr	tr
chlorite, epidote	10	--
	100	100

Major Oxides (percent)	S78-73b	Calc-alk.[4] andesite	Hawaii[5] tholeiite	Oceanic[6] tholeiite
SiO_2	52.8	58.65	49.4	49.34
TiO_2	1.0	0.79	2.9	1.47
Al_2O_3	17.2	17.43	13.9	17.04
Fe_2O_3	1.9	3.21	3.0	1.99
FeO	5.5	3.48	8.5	6.82
MnO	0.15	0.10	0.2	0.17
MgO	4.8	3.28	8.4	7.19
CaO	9.7	6.26	10.3	11.72
Na_2O	2.4	3.82	2.1	2.73
K_2O	0.5	1.99	0.4	0.16
H_2O^+	1.2	1.06	--	0.69
	97.15	100.07	98.5	99.34

Trace Elements (ppm)	S78-73a	S78-73b	Threshold[7] Pac. NW	(-) less than
Ag	0.3	0.6	-0.1	
Cu	165	130	50	
Mo	2	-1	-1	
Pb	30	10	20	
Zn	40	30	60	

[1]SW 1/4 sec. 7, T. 3 N., R. 5 E.; [2]NW 1/4 sec. 18, T. 3 N., R. 5 E.; [3]apatite, sphene; [4]McBirney, 1969, p. 503; [5]MacDonald and Abbott, 1970, p. 113; [6]Engel and others, 1965, p. 721; [7]Field and others, 1974, p. 17.

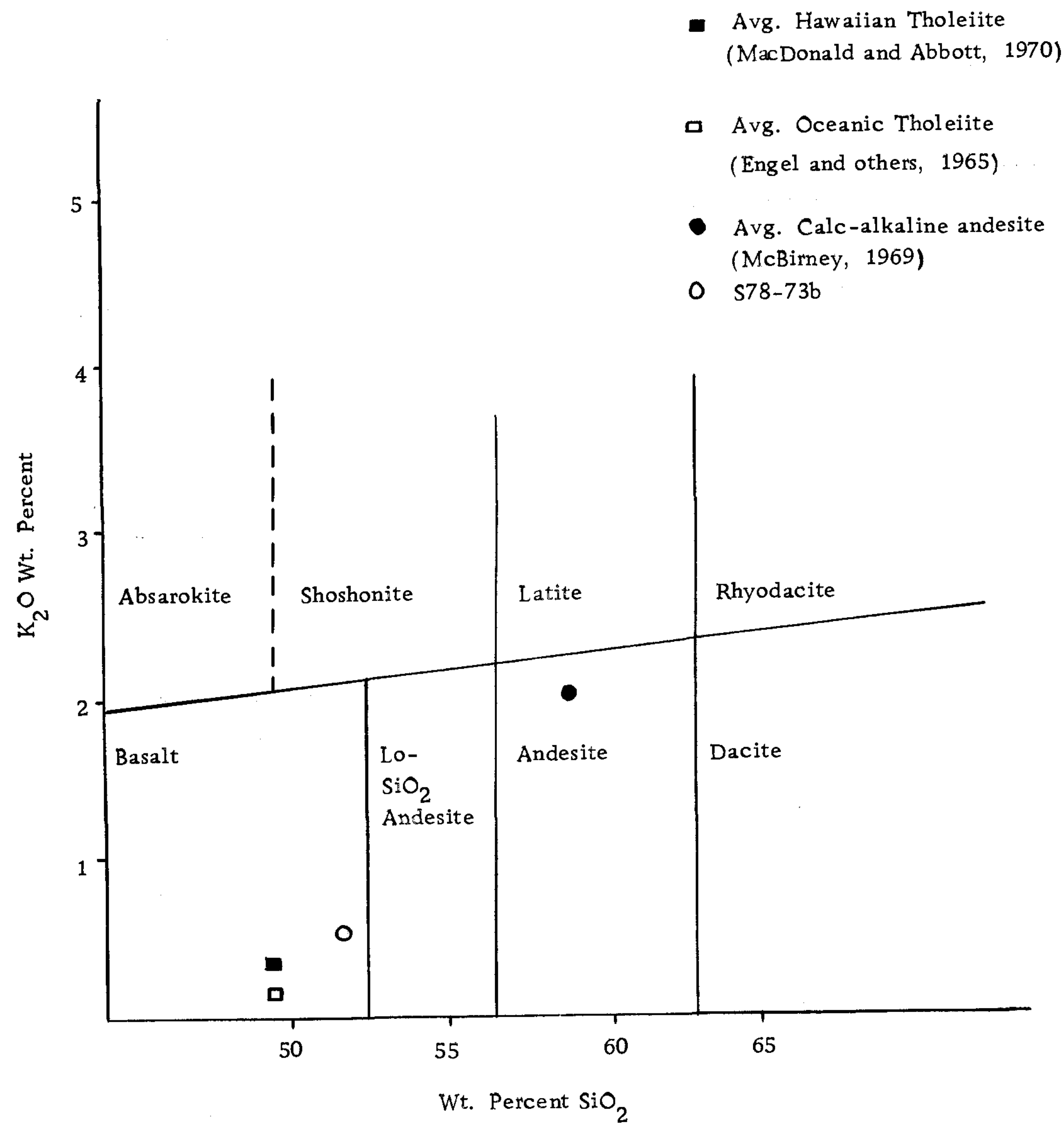

Figure 3. Chemical classification of a Skamania formation flow rock (After MacKenzie and Chappell, 1972).

closely approximates the threshold values suggested by Field and others (1974) for the Pacific Northwest. However, this small number of analyses from a single sample cannot be considered representative of the entire formation.

The major oxide chemical analysis of one specimen from a flow unit of the Skamania formation is plotted on Figure 3. Also plotted for comparison is an average for calc-alkaline andesites (McBirney, 1969), an average for oceanic tholeiitic basalts (Engel, Engel, and Havens, 1965), and an average for Hawaiian tholeiitic basalts (MacDonald and Abbott, 1970).

The chemical analysis of the specimen of Skamania formation basalt plots near the average Hawaiian tholeiite in Figure 3. In addition, the Skamania rock exhibits Fe_2O_3/FeO and Na_2O/K_2O ratios that are broadly similar to those of Hawaiian tholeiite. Thus, it is suggested that the magma source for the Skamania flow is compositionally primitive and has not undergone significant fractionation. Also, the magma has not been contaminated by more silicic material in its rise to the surface.

Origin

The lack of pillow structures, and the occasional columnar jointing in the mafic flows of the Skamania formation indicate subaerial conditions prevailed at the time of deposition. In addition, Schriener (1979) has reported fossil wood fragments in a volcaniclastic portion of this formation, which also suggests that subaerial conditions prevailed at the time these volcanics were extruded.

Correlation and Age

Definite stratigraphic marker beds, such as the Stevens Ridge Formation (Fiske, Hopson, and Waters, 1963; Hammond, 1974), are lacking in the Washougal district, and thus hamper reliable regional correlation of the Skamania formation. It is tentatively suggested, however, that the Skamania formation correlates with the Fifes Peak Formation of Fiske, Hopson, and Waters (1963), Simon (1972), and Hartman (1973) on the basis of similarities in age, stratigraphic position, and lithology.

Indirectly, it is possible to establish an age span for the Skamania formation. The underlying East Fork formation (Ohanapecosh Formation) is intruded by the Silver Star Stock. The age of the East Fork is bracketed between late Eocene and middle Oligocene epochs. Intrusive bodies of the Washington Cascades generally range in age from middle Eocene to early Miocene (Armstrong and others, 1976; Sutter, 1978). Thus, the Silver Star Stock is probably Middle Oligocene to early Miocene in age. The nearest intrusion is in the Camp Creek Mining District of northern Skamania County. It has been dated by the K/Ar method at 24 m. y. old, according to

Armstrong and others (1976).

The Skamania formation overlies the Silver Star stock, and the lowermost units of the formation have been hornfelsed by the intrusion. Therefore, the Skamania formation was presumably partly deposited when emplacement of the intrusive magma occurred. Thus, at least the basal flows of the Skamania formation were present between middle Oligocene to early Miocene epochs.

On the basis of stratigraphic position, Fiske, Hopson, and Waters (1963) assigned the Fifes Peak Formation to the interval ranging from middle Oligocene to late Miocene time. Hartman (1973) has reported whole rock radiometric dates of 22, 23, 17, and 20 m.y. for rocks of the Fifes Peak Formation. These dates confirm the estimate of an early Miocene age for this formation. Thus, ages assigned to the Skamania formation and that of the Fifes Peak Formation are roughly correlative.

The Fifes Peak Formation is a sequence of porphyritic andesite and basalt flows having minor, poorly sorted, epiclastic volcanic interbeds. It was first defined by Warren (1941) as a part of the "upper Keechelus" of Smith and Calkins (1906). Later, Hartman (1973) found it to unconformably overlie the Ohanapecosh Formation in the southwest part of the Greenwater River area. Simon (1972) reported andesite dikes intruding the Ohanapecosh Formation in the Camp Creek area, and assigned them to the Fifes Peak Formation.

The formation, therefore, has been reported as far south as northern Skamania County, and has been shown to have an unconformable relationship to the Ohanapecosh Formation in at least one area.

The porphyritic flows of the Fifes Peak Formation constitute approximately 80 percent of its exposures. These flows contain phenocrysts of plagioclase feldspar, augite, and hypersthene in an intergranular to intersertal texture. Consequently, the term "basaltic andesite" was deemed appropriate (Fiske, Hopson, and Waters, 1963). The abundances of the various ferromagnesian minerals was found to be variable in some flows. The flows have been only slightly to moderately altered, and contain clay minerals, carbonate, and rare epidote. Incipient spherulitic structures appear in the devitrified glass. Thus, similarities between rocks of the Skamania formation and those of the Fifes Peak Formation are indicated by the range of plagioclase feldspar compositions, abundance of flow rocks in the formation as a whole, and the intensity and types of alteration minerals.

Mafic Dikes

Intrusive mafic dikes were observed crosscutting the East Fork formation, the Silver Star stock, and possibly the Skamania formation. They generally trend northwest and form nearly vertical, resistant ridges of one to three meters in width. Fresh samples range from dark greenish gray (5G 4/1) to medium gray (N5) in color, and from aphanitic to moderately porphyritic. Visible phenocrysts are plagioclase feldspar and hornblende as lath-shaped subhedra.

All mafic dikes were crosscut by irregular veinlets of epidote, hematite, quartz, and K-feldspar. These varied from one to ten centimeters in width. Near the northeast corner of sec. 10, T. 3 N., R. 5 E., a local zone of intrusive breccia associated with a mafic dike was observed. This breccia is confined within rocks inferred to be part of the Skamania formation. At another location (SW. 1/4 sec. 16, T. 3 N., R. 5 E.), a mafic dike within the Silver Star stock is intruded by a veinlet of granitic aplite about one centimeter in width.

INTRUSIVE ROCKS

The largest intrusion in the Washougal Mining District was first called the "Silver Star Formation" by Allen (1932). Felts (1939a) conducted a brief petrographic examination of the stock, and found that it consisted of granodiorite, with subordinate amounts of augite diorite and quartz diorite developed near the periphery. Felts also mentioned the presence of small aplite dikes within the stock, and indicated that "small spots of granodiorite" were exposed in the southeastern portion of the area. Schriener (1979) designated the stock the Silver Star Plutonic Complex (SSPC) in his study of the northern part of the Washougal district and prescribed seven separate intrusive plutonic phases.

The Silver Star stock is exposed over an area of approximately 20 square miles (52 sq. km). Small outlying cupolas add only one square mile to this total. A large proportion of the stock is characterized by steep talus slopes, with rare outcrops on ridgetops and in stream valleys. The cupolas are exposed only at roadcuts.

The Silver Star stock is classified as a shallow level epizonal intrusion, in accordance with the classification of Buddington (1959). Some of the characteristics exhibited by the stock are: (1) sharp, discordant contacts between the volcanic country rock and the intrusion; (2) a contact metamorphic aureole; (3) chilled contacts within the margin of the stock; (4) intrusive breccia pipes; (5) composite intrusive history; and (6) granophyric textures.

Felts (1939a) concluded that doming and forceful deformation of the country rock was secondary to stoping in the emplacement process of the Silver Star stock. Evidence supporting this conclusion may be found in the fact that the overlying flow units of the Skamania formation are essentially horizontal, and have not been tilted or deformed. Also, resorbed xenoliths are common near the contact of the stock and the adjacent country rock, suggesting that some minor assimilation has occurred.

The Silver Star stock intrudes the East Fork formation. The age of this formation is bracketed between late Eocene and middle Oligocene epochs (p. 23). Thus, the stock must be at least post-middle Oligocene in age. Intrusive stocks and plutons of the Washington Cascade Range vary in age from middle Eocene through early Miocene (Armstrong and others, 1976). Consequently, the Silver Star stock is inferred to have been emplaced between middle Oligocene to early Miocene time.

On the basis of contact relationships observed in and around the Silver Star stock, the order of emplacement of the various intrusive phases is as follows: (1) intrusive andesite; (2) diorite; (3) quartz diorite; (4) granodiorite; (5) vesicular porphyritic quartz diorite; and (6) granitic aplite. Plutonic rock names are assigned in accordance with the IUGS classification system, as described by Streckeisen

(1976). Descriptions of the various phases follow.

Intrusive Andesite

Two small cupolas of intrusive andesite intrude the East Fork formation in upper Dougan Creek, southeast of the main body of the Silver Star Stock (Plate 1). The andesite accounts for approximately five percent of the intrusive rocks in the study area. Samples of the andesite on weathered surfaces are grayish orange (10 YR 7/4), and are greenish gray (5G 6/1) on fresh surfaces. The modal color index is five to eight percent. The rock is porphyritic, with phenocrysts of plagioclase feldspar and pyroxene visible in hand specimen. Orbicular texture is developed locally, especially in the northernmost cupola.

Petrographic examination reveals the andesite to have a porphyritic hypocrystalline texture, with phenocrysts totalling 40 to 55 percent of the rock. Flow textures or mineral alignment are not present. Modal analyses of two samples, and a chemical analysis of one sample are listed in Table 4.

Phenocrysts of the plagioclase feldspar have subhedral to euhedral outlines, and form narrow laths averaging one millimeter in width and two millimeters in length. They are twinned by the Albite, and less frequently by the Carlsbad twinning laws. Composition of the plagioclase is An_{62-66}, determined by the Michel-Levy and

Table 4. Modal mineral, trace element, and major oxide analyses for rocks of the intrusive andesite.

Minerals (percent)	S78-5[1]	S78-98[2]
Plagioclase feldspar	34	31
Cpx (augite)	5	6
Interstitial matl.[3]	33	34
Chlorite, epidote	21	16
Orbicules[5]	6	12
Opaques	tr	tr
Accesory mins.[6]	tr	tr
	100	100

Major Oxides (percent)	S78-5	"gabbrodiorite"[7]
SiO_2	54. 9	52. 5
TiO_2	1. 2	0. 9
Al_2O_3	16. 1	18. 2
Fe_2O_3	1. 7	--
FeO	5. 8	8. 4
MnO	0. 14	0. 1
MgO	4. 9	5. 4
CaO	7. 8	7. 5
Na_2O	2. 3	2. 6
K_2O	1. 3	0. 6
H_2O+	1. 9	--
	98. 04	98. 3

Trace Elements (ppm)	S78-5	Threshold[8] Pac. NW	(-) less than
Ag	0. 7	-0. 1	
Cu	130	50	
Mo	2	-1	
Pb	25	20	
Zn	75	60	

[1]NE 1/4 sec. 33, T. 3 N., R. 5 E.; [2]SE 1/4 sec. 28, T. 3 N., R. 5 E.; [3]Alt. glass, chlorite, clays, quartz; [4]Alt. of plagioclase; [5]Concentric layers of quartz, chlorite, and epidote; [6]Apatite, sphene; [7]Erikson, 1969, p. 2220; total iron reported as FeO; [8]Field and others, 1974, p. 17.

combined Carlsbad-Albite methods (Kerr, 1959). Faint normal zoning is present, with compositions of the zones ranging from An_{62} to An_{66}. The phenocrysts of plagioclase feldspar are commonly replaced by chorite and (or) epidote.

Phenocrysts of pyroxene consist of subhedral to euhedral clinopyroxene, probably augite. They average one millimeter in width and two millimeters in length. Twins are regularly observed. Alteration has produced clots of chlorite, with or without scattered anhedral magnetite.

The groundmass of the intrusive andesite is aphanitic, and is altered to dark brown unidentified clay. The subspherical orbicules noted in the northern cupola appear randomly scattered throughout the groundmass. They are one to three mm in diameter, and exhibit concentric layer of quartz, chlorite, and epidote (not necessarily in order). These alteration minerals constitute five percent of the rock. A few euhedral pyrite crystal are also found in the orbicules.

Also listed in Table 4 are the trace element and major oxide chemical analyses of a single specimen of the intrusive andesite. The major oxide chemistry is compared to that of the average "gabbro-diorite" from the Snoqualmie batholith in the central Washington Cascades (Erikson, 1969, p. 2220).

The intrusive andesite is somewhat more enriched in SiO_2, TiO_2, and K_2O than the average "gabbro-diorite" from the Snoqualmie

Batholith (Erikson, 1969). The higher amounts of silica and potassium in the Silver Star intrusive andesite would suggest that the andesite is more fractionated than the gabbro-diorite. However, the results could also be affected by late hydrothermal alteration of the andesite. Evidence for such alteration is found in the presence of quartz and epidote-bearing orbicules that are variably present in the andesite intrusions.

Diorite

One small outcrop of porphyritic diorite is located in the extreme northwest corner of sec. 27, T. 3 N., R. 5 E., where it has intruded the volcanic rocks of the East Fork formation. It appears to be a sill-like intrusion, although the overlying strata are no longer present. The rock is considered to be an intrusive phase on the basis of its nearly holocrystalline character. In outcrop, the diorite does not differ significantly from exposures of the underlying East Fork flow units, and its unique coarsely crystalline character is noticeable only upon close examination.

Hand specimens of the diorite vary in color from brownish gray (5YR 4/1) on weathered surfaces, to light gray (N7) to dark greenish gray (5G 4/1) on fresh surfaces. Phenocrysts of plagioclase feldspar, pyroxene, and, rarely, magnetite are discernible to the unaided eye. The largest plagioclase phenocrysts measure up to seven millimeters in length and four millimeters in width, but average phenocrysts are less than one-half this size. Phenocrysts of pyroxene are up to four millimeters in length, whereas those of magnetite are less than one millimeter in diameter.

Petrographic studies indicate the diorite to have a porphyritic intergranular texture. The results of modal analysis are listed in Table 5. Subhedral plagioclase feldspar phenocrysts commonly are twinned by the Albite law, and normal zoning is frequently present. Compositions of the plagioclase phenocrysts range from An_{61} in the cores, to An_{52} at the rims. The phenocrysts commonly exhibit a tendency toward glomeroporphyritic texture. They are almost entirely unaltered, although thin alteration veinlets of anhedral quartz and epidote less than one millimeter wide may crosscut the specimens.

The pyroxene phenocrysts are clinopyroxene, probably augite. They are commonly twinned, and one cross-section exhibited faint concentric zoning when rotated to partial extinction. The clinopyroxene may be partially to completely altered to chlorite, with or without magnetite. In addition, magnetite is present as interstitial subhedra up to one millimeter in diameter. Table 5 lists the modal and major oxide chemical analyses of the average diorite from the northern part of the Washougal Mining District (Schriener, 1979, p. 35). In addition, the major oxide chemical analysis of the average "gabbro-diorite" from the Snoqualmie Batholith is listed (Erikson, 1969,

Table 5. Modal mineral, trace element, and major oxide analyses for a sample of diorite.

Minerals (percent)	S78-97[1]	Avg. diorite, N. Washougal dist.[2]
Quartz	3	3
Plagioclase feldspar	65	65
Cpx (augite)	8	5
Opx	--	7
Opaques	4	3
Apatite, sphene	tr	tr
chlorite, epidote, clay[5]	20	17
	100	100

Major Oxides (percent)	S78-97	Rep. diorite, N. Washougal[2]	"gabbrodiorite"[3]
SiO_2	58.5	52.6	52.5
TiO_2	0.6	1.3	0.9
Al_2O_3	15.9	18.2	18.2
Fe_2O_3	2.7	--	--
FeO	4.5	8.4	8.4
MnO	--	--	0.1
MgO	3.7	5.5	5.4
CaO	6.8	8.5	9.5
Na_2O	3.2	3.9	2.6
K_2O	1.6	0.6	0.6
H_2O^+	--	--	--
	97.5	99.1	98.3

Trace Elements (ppm)	S78-97	Threshold[4] Pac. NW	(-) less than
Ag	-0.2	-0.1	
Cu	95	50	
Mo	4	-1	
Pb	5	20	
Zn	60	60	

[1]NW 1/4 sec. 27, T. 3 N., R. 5 E.; [2]Schriener, 1979, p. 35: total iron reported as FeO; [3]Erikson, 1969, p. 2220: total iron reported as FeO; [4]Field and others, 1974, p. 17; [5]Alt. of glass, plagioclase and pyroxenes less than 0.25 mm diameter.

p. 2220).

Although the modal analyses of diorites from the northern and southern parts of the Silver Star stock are strongly correlative, their respective major oxide analyses exhibit marked differences. Particularly noteworthy is the higher content of SiO_2 and K_2O in the diorite from the southern part of the stock. This rock has been slightly altered (crosscutting veinlets of quartz and epidote), and therefore the analysis may not reflect the true chemistry of this igneous rock.

Quartz Diorite

Quartz diorite constitutes approximately 25 percent of the Silver Star stock in the study area. Samples of the rock appear light olive (5Y 4/1) to light brownish gray (5YR 6/1) on weathered surfaces, and are medium gray (N5) on fresh surfaces. Exposures of the quartz diorite are best observed along the "central ridge," paralleling the eastern margin of the stock. However, outcrops of this intrusive phase are rare, as talus slopes predominate on the ridgetops and hill sides.

The quartz diorite has a hypidiomorphic porphyritic texture that normally is associated with an intergranular groundmass. The phenocrysts include plagioclase feldspar and clinopyroxene. The groundmass is composed of plagioclase, clinopyroxene, quartz, and accessory and alteration minerals. Orthoclase is present in trace amounts. Results of modal analyses of four quartz diorite samples are listed in Table 6. Also listed is the mineral composition of average quartz diorite from the northern part of the Silver Star stock (Schriener, 1979, p. 38).

Quartz forms anhedral interstitial masses in the groundmass of the quartz diorite. Small fluid inclusions are common in the quartz, and normally contain a liquid phase, a gaseous phase of lesser volume, and, rarely, a cubic daughter salt. Orthoclase is infrequently observed as anhedral interstitial masses associated with the quartz.

Plagioclase feldspar phenocrysts are subhedral, and range in composition from An_{45} to An_{55}. Faint normal zoning is present, with the compositions of the zones falling within the stated range. Plagioclase in the groundmass is usually unzoned, and is slightly more calcic (one percent An) than are the cores of the larger phenocrysts. In general, a minor degree of alteration of the feldspar has produced epidote, chlorite, and unidentified clays. Plagioclase phenocrysts average one millimeter by three millimeters in size, and plagioclase in the groundmass averages one millimeter or less in maximum dimension.

Clinopyroxene in the quartz diorite is extensively altered, and is commonly replaced by anhedral masses of uralite, chlorite, magnetite, and minor amounts of biotite. The term uralite is used to

Table 6. Modal mineral, trace element, and major oxide analyses for samples of quartz diorite.

Minerals (percent)	S78-66[1]	S78-70[2]	S78-87[3]	S78-124[4]	Avg. N. Wash. dist.[5]
Quartz	2	9	6	14	9
Mym. txt.[6]	--	--	29	--	--
Plagioclase	83	66	51	68	64
Cpx (augite)	4	tr	--	tr	6
Opx	--	tr	--	--	tr
Uralite	--	19	6	12	--
Biotite	tr	tr	tr	2	tr
Opaques	3	4	2	3	4
Acc. Mins.[7]	tr	tr	1	tr	tr
Alt. Mins.[8]	7	tr	5	tr	16
	100	100	100	100	100

Major Oxides (percent)	S78-70	S78-124	"Basic Phase"[9]	Avg. N. Wash. dist.[5]	Avg. micro-diorite Crbn. Rvr. Stock[10]
SiO_2	58.3	60.3	58.1	57.6	55.0
TiO_2	1.1	0.9	0.6	0.9	1.1
Al_2O_3	17.0	17.2	16.5	18.0	13.1
Fe_2O_3	3.2	2.9	--	--	2.3
FeO	3.1	3.4	6.7	6.9	6.4
MnO	0.14	0.11	0.17	--	0.13
MgO	3.6	3.2	4.9	3.8	4.0
CaO	6.6	6.2	7.3	7.0	7.2
Na_2O	4.3	4.0	3.3	4.2	3.7
K_2O	1.4	0.9	0.6	0.9	1.2
H_2O^+	0.4	0.5	0.7	--	1.5
	99.14	99.61	98.0	99.3	95.5

Trace Elements (ppm)	S78-70	S78-124	Avg. N. Wash. dist.[5]	Threshold Pac. NW[11]	(-) less than
Ag	0.4	0.3	0.4	-0.1	
Cu	50	18	75	50	
Mo	2	1	2	-1	
Pb	20	8	7	20	
Zn	65	30	37	60	

[1]NW 1/4 sec. 16, T. 3 N., R. 5 E.; [2]SE 1/4 sec. 20, T. 3 N., R. 5 E.; [3]NE 1/4 sec. 19, T. 3 N., R. 5 E.; [4]NE 1/4 sec. 20, T. 3 N., R. 5 E.; [5]Schriener, 1979, p. 38; total iron reported as FeO; [6]Myrmekitic texture; [7]Sphene, zircon, apatite, tourmaline; [8]Clays, sericite, epidote, chlorite; [9]Felts, 1939a, p. 309; total iron reported as FeO; [10]Fischer, 1970, p. 130; [11]Field and others, 1974, p. 17.

indicate a pale green, faintly pleochroic amphibole formed at the expense of pyroxene. Its finely-crystalline form precludes more accurate identification. A detailed discussion of uralitic alteration is provided by Fischer (1970). He notes that the optical properties of uralite are variable, indicating minor chemical differences dependent upon the host mineral. Also, the formation of uralite is regularly accompanied by development of anhedral magnetite and brown biotite (Fischer, 1970, p. 165).

Sample S78-87 (NE 1/4 sec. 19, T. 3 N., R. 5 E.) is a porphyritic quartz diorite that has been subjected to extensive silicification and deuteric alteration (Enlows, 1979, oral communication). Myrmekitic intergrowths of quartz and plagioclase compose nearly one-third of the rock. Primary pyroxenes have been replaced by hornblende and uralite, accompanied by a small amount of biotite and magnetite. A few scattered tourmaline rosettes are also present. Fluid inclusions in quartz may contain up to two solid daughter phases, in addition to the liquid and gaseous phases. Compositions of plagioclase feldspar range from An_{45} to An_{36} from core to rims.

Major oxide and trace element chemical analyses are listed in Table 6. Also listed are the analyses of Felts (1939a) "basic phase" from the Silver Star stock, the average quartz diorite from the northern part of the Silver Star stock (Schriener, 1979, p. 38), and the average of two "micro-quartz diorites" from the Carbon River stock in the central Washington Cascades (Fischer, 1970, p. 130). Trace element analyses are compared to the threshold levels suggested by Field and others (1974) for the Pacific Northwest.

It may be seen from Table 6 that the major oxide chemistry of quartz diorites from the northern and southern parts of the Silver Star stock are in reasonable agreement with one another. Variations in the intensity and type of alteration could easily explain the minor differences observed in SiO_2, Al_2O_3, and K_2O. It appears that the rocks from the southern part of the stock have experienced slight enrichment in SiO_2 and K_2O, and have lost Al_2O_3 and CaO, in reference to the average quartz diorite from the northern area. The "basic phase" of Felts (1939a) also shows major oxide chemistry similar to the range of the quartz diorites.

Granodiorite

Granodiorite composes approximately 70 percent of the Silver Star stock within the study area. Samples from outcrops of the granodiorite are light gray (N7) to pale red purple (5RP 6/2), weathering to light gray (N6) to light brownish gray (5YR 6/1). The granodiorite is best exposed along stream valleys and road cuts, as loose talus slopes predominate the hillsides and ridgetops. Numerous xenoliths are contained in the granodiorite near the contacts with the quartz diorite and the volcanic country rocks.

The dominant texture exhibited by the granodiorite is hypidiomorphic equigranular. In addition, myrmekitic and granophyric intergrowths are observed in some specimens. The granodiorite is composed of subhedral plagioclase feldspar and hornblende, surrounded by interstitial masses of quartz and orthoclase. Clinopyroxene is the major mafic mineral near the margins of the granodiorite, rather than hornblende. Accessory minerals include apatite, sphene, zircon, and rare rosettes of tourmaline. Modal analyses of four specimens from the Silver Star stock are listed in Table 7. Also listed is the average granodiorite from the northern part of the Silver Star stock (Schriener, 1979, p. 43).

Two anomalous specimens are included in the granodiorite suite of rocks, and are not separtely mapped on Plate 1. Petrographic examination revealed sample S78-120 to be an equigranular quartz monzodiorite (SW 1/4 sec. 20, T. 3 N., R. 5 E.), and sample S78-50B proved to be a slightly orthoclase-rich quartz diorite (NW 1/4 sec. 6, T. 2 N., R. 5 E.).

Quartz is present as interstitial anhedra between the plagioclase and hornblende crystals of the granodiorite, and usually contains minute fluid inclusions. The inclusions contain a liquid and a gaseous phase in varying proportions, and up to two separate daughter salts (probably halite and sylvite).

Orthoclase commonly is localized in interstitial areas, in

Table 7. Modal mineral, trace element, and major oxide analyses for samples of granodiorite.

Minerals (percent)	S78-50b[1]	S78-50c[2]	S78-94[3]	S78-120[4]	Avg. N. Wash. dist.[5]
Quartz	7	18	23	10	20
Orthoclase	3	17	22	7	13
Plagioclase	47	41	42	52	48
Mym. txt.[6]	--	--	--	10	--
Cpx (augite)	7	—	--	--	--
Uralite	23	--	--	--	--
Hrnblnd.	--	12	5	13	8
Biotite	7	tr	tr	3	2
Opaques	5	3	2	2	3
Acc. Mins.[7]	tr	tr	tr	tr	tr
Alt. Mins.[8]	tr	8	5	3	2
	100	100	100	100	96

Major Oxides (percent)	S78-94	S78-120	"acid phase"[9]	Avg. N. Wash. dist.	Snoqualmie Bath.[10]
SiO_2	65.9	61.8	65.9	64.6	65.6
TiO_2	0.8	1.0	0.45	0.7	0.5
Al_2O_3	14.9	15.9	15.72	15.3	15.7
Fe_2O_3	1.6	2.4	1.11	--	--
FeO	2.6	3.4	3.05	4.8	4.5
MnO	0.085	0.1	0.06	--	0.1
MgO	1.9	2.7	2.39	1.8	2.3
CaO	3.9	5.1	4.78	4.4	4.5
Na_2O	3.5	3.6	3.62	4.4	3.4
K_2O	2.5	1.9	1.94	2.2	2.3
H_2O^+	0.4	0.6	0.76	--	--
	98.085	98.5	98.96	98.2	98.8

Trace Elements (ppm)	S78-94	S78-120	Avg. N. Wash. dist.[5]	Threshold Pac. N. W.[11]
Ag	0.4	0.3	0.3	-0.1
Cu	75	125	31	50
Mo	2	1	2	-1
Pb	20	7	8	20
Zn	45	30	16	60

[1,2]NW 1/4 sec. 6, T. 2 N., R. 5 E.; [3]NW 1/4 sec. 16, T. 3 N., R. 5 E.; [4]Quartz monzodiorite, SW 1/4 sec. 20, T. 3 N., R. 5 E.; [5]Schriener, 1979, p. 43; total iron reported as FeO; [6]Myrmekitic texture; [7]sphene, apatite, zircon, tourmaline; [8]Chlorite, epidote, sericite, clays, carbonate; [9]Felts, 1939a, p. 309; [10]Erikson, 1969, p. 2220; [11]Field and others, 1974, p. 17.

fractures developed within plagioclase crystals, or in micrographic intergrowths with quartz. The orthoclase is generally "dusty" in appearance, which helps to distinguish it optically from the relatively clear quartz.

The plagioclase feldspar in the granodiorite is subhedral, one to two millimeters in length, and one-half to one millimeter in width. Compositions range from An_{46} in the cores of zoned crystals, to An_{34} at the rims. Such normal zoning is relatively common. Quartz is frequently found in vermicular intergrowths (myrmekite) along the rims of the plagioclase crystals. The plagioclase is slightly altered to epidote, sericite, and traces of carbonate.

Primary hornblende is the most common mafic mineral in the granodiorite of the Silver Star stock. Uralitized pyroxenes also compose a small portion of the mafic minerals, and are invariably associated with anhedral magnetite and ragged patches of biotite. The hornblende crystals average 0.5 mm in width, and 1.0 mm in length, and they are usually subhedral in shape. Twins are commonly observed. Chlorite is present as an alteration product of hornblende, uralite, and biotite.

Major oxide and trace element analyses of two granodiorite samples are listed in Table 7. Also listed are the average analysis of granodiorite from the northern part of the Silver Star stock (Schriener, 1979, p. 43), the average granodiorite analysis from the Snoqualmie batholith (Erikson, 1969, p. 2220), the analysis of the "acid phase" of the Silver Star stock from Felts (1939a), and the background values for trace elements in the Pacific Northwest (Field and others, 1974).

The major oxide chemistries of granodiorite from the southern and northern parts of the Silver Star stock, and the "acid phase" of Felts (1939a), exhibit excellent agreement with each other. In addition, the average granodiorite from the Snoqualmie batholith is also chemically similar to that of the Silver Star stock.

The slight variation in major oxide chemistries of specimens S78-94 and S78-120 is reflected by differences between their respective modal analyses. Specimen S78-94 exhibits higher amounts of SiO_2 and K_2O, and has significant amounts of quartz and orthoclase. Sample S78-120 contains less SiO_2 and K_2O, and also contains less quartz and orthoclase in the modal analysis. In addition, S78-120 has substantially more Al_2O_3 and CaO than does S78-94, which is consistent with its greater content of plagioclase feldspar. The reasonably close correlation between major oxide chemistries and modal analyses suggests that these intrusive rocks formed under near equilibrium conditions from the same magma.

Vesicular Porphyritic Quartz Diorite

The vesicular porphyritic quartz diorite intrudes the Silver Star granodiorite, and is exposed in the bottom of Copper Creek (SW 1/4 sec. 8, T. 3 N., R. 5 E.). It composes an estimated five percent of the Silver Star stock in the study area. Numerous xenoliths of the granodiorite are included near the margins of the vesicular porphyritic quartz diorite. Hand specimens are light bluish gray (5B 7/1) on fresh surfaces, becoming yellowish gray (5Y 8/1) to light olive gray (5Y 6/1) on weathered surfaces. Phenocrysts constitute six to ten percent of the rock, and include plagioclase feldspar and chloritized hornblende. Three to five percent of the rock consists of subspherical vesicles averaging one millimeter in diameter, although a few are up to four millimeters in diameter. The smaller vesicles are frequently filled with quartz and thus are amygdules. In general, the vesicles tend to become less abundant and smaller near the margins of the intrusion.

Quartz is present as an interstitial mineral. It contains a small number of fluid inclusions that consist of liquid and vapor phases. The liquid phase predominates, and solid daughter products were not observed.

The plagioclase feldspar in the vesicular porphyritic quartz diorite forms large euhedral phenocrysts up to three millimeters in length. They are contained in a pilotaxitic groundmass comprised of plagioclase laths, hornblende, chlorite, magnetite, pyrite, and interstitial quartz. Compositions of the plagioclase feldspar range from An_{38} to An_{45} with faint normal zoning. Alteration products associated with the plagioclase feldspar include substantial quantities of sericite and carbonate and a minor amount of epidote.

Primary hornblende phenocrysts, commonly twinned, average one millimeter by three millimeters in size. They are variably replaced by chlorite and magnetite. Smaller hornblende crystals are in the groundmass as subhedra up to one millimeter in length. They commonly form nearly circular crystalline mosaics up to five millimeters in diameter that have been largely chloritized.

Accessory minerals include pyrite, which contains trace amounts of chalocpyrite and covellite visible under reflected light. Tourmaline is also present in trace amounts.

Major oxide and trace element chemical analyses for one specimen of vesicular porphyritic quartz diorite are given in Table 8, as are those of a representative quartz diorite porphyry from the northern part of the Washougal district (Schriener, 1979, p. 47). The vesicular porphyritic quartz diorite is chemically similar to the quartz diorite porphyry from the northern area. These geographically distinct samples probably represent the same intrusive phase of the Silver Star stock.

It is of interest to note that this porphyritic phase is associated with mineralization in the northern part of the stock. Similar late-stage intrusions have been reported in many hydrothermal systems

Table 8. Modal mineral, trace element, and major oxide analyses for samples of vesicular porphyritic quartz diorite.

Minerals (percent)	S78-81b[1]	S78-81d[2]	Avg. N. Wash. dist.[3]
Quartz	6	11	5
Orthoclase	--	--	--
Plagioclase	64	57	64
Hornblende	15	tr	8
Opaques	3	3	6
Acc. mins.[4]	tr	tr	--
Hbld. alt.[5]	7	11	--
Plag. alt.[6]	4	15	6
	100	100	89

Major Oxides (percent)	S78-81b	Rep., N. Wash. dist.[3]
SiO_2	58.9	59.1
TiO_2	0.8	1.0
Al_2O_3	16.8	16.1
Fe_2O_3	2.4	--
FeO	4.2	6.4
MnO	0.092	--
MgO	3.6	4.3
CaO	4.0	6.6
Na_2O	4.4	5.9
K_2O	1.7	0.4
H_2O^+	1.2	--
	98.092	99.8

Trace Elements (ppm)	S78-81b	Rep., N. Wash. dist.	Threshold Pac. NW[7]
Ag	0.3	0.4	-0.1
Cu	390	670	50
Mo	2	2	-1
Pb	25	6	20
Zn	60	25	60

[1,2] SW 1/4 sec. 8, T. 3 N., R. 5 E.; [3] Schriener, 1979, p. 47: total iron reported as FeO; [4] Sphene, zircon, apatite, tourmaline; [5] Chlorite, magnetite; [6] Carbonate, sericite, epidote, clays; [7] Field and others, 1974, p. 17.

(Erikson, 1969; Gustafson and Hunt, 1975; Soregaroli and Brown, 1976; Wilson, 1978). The anomalous copper content of these porphyritic quartz diorites and their vesicular texture suggest a close genetic as well as spatial relationship between magmatic and hydrothermal activity.

Granitic Aplite

Narrow dikes of granitic aplite crosscut all phases of the main body of the Silver Star stock. The dikes vary from one to thirty centimeters in width, and exhibit no preferred orientation. Their small size precludes accurate representation on Plate 1 and consequently they cannot be shown on the map.

The aplite is pale red purple (5RP 6/2) on fresh exposures, and is pale red (5R 6/2) on weathered surfaces. The aplite dikes are fine-grained near their outer margins and become pegmatitic toward the center. The predominant minerals visible in hand specimen are quartz and orthoclase, with individual crystals averaging up to one millimeter in diameter.

Petrographic examination reveals that the pegmatitic cores of the aplite dikes lack graphic textures, and usually form an anhedral mosaic of quartz and microperthitic orthoclase. A few subhedral plagioclase feldspar crystals (An_{30-34}) are present. Finely crystalline muscovite (sericite) is scattered throughout the aplite dikes, and is usually interstitial. A small number of euhedral pyrite crystals are present in the cores of the dikes. Quartz frequently contains fluid inclusions. They contain a liquid phase, a gaseous phase of lesser volume, and in one instance three separate solid daughter salts.

The modal mineralogy and major oxide and trace element chemical analyses of one specimen of granitic aplite are listed in Table 9. Also included for comparison are the average of modal and chemical analyses of aplitic rocks from the northern part of the Silver Star stock (Schriener, 1979, p. 53), and from the Snoqualmie Batholith (Erikson, 1969, p. 2224).

The granitic aplite from the southern part of the Silver Star stock has substantially less SiO_2 and K_2O than the aplites from the northern part of the stock, or from the Snoqualmie Batholith. In addition, the higher Al_2O_3 and CaO content of aplite from the southern Silver Star stock suggests that plagioclase feldspar should be an important mineral in the modal analysis. However, it appears that subsequent hydrothermal alteration has leached silica and potash from the rock, with concomitant replacement of plagioclase feldspar with sericite.

Petrochemistry

Many workers have suggested that a co-magmatic relationship exists between near surface volcanic rocks and deep intrusives (Fiske,

Table 9. Modal mineral, trace element, and major oxide analyses for a sample of granitic aplite.

Minerals (percent)	S78-116[1]	Rep., N. Wash. dist.[2]	Avg. aplite[3] Snoqualmie Batholith
Quartz	43	38	38
Orthoclase[4]	40	40	39
Plagioclase	3	10	23
Muscovite	13	2	--
Biotite	--	--	tr
Opaques	tr	tr	tr
Acc. mins.[5]	tr	4	tr
Alt. mins.[6]	tr	5	--
	100	100	100

Major Oxides (percent)	S78-116	Rep., N. Wash. dist.	Avg. aplite Snoqualmie Batholith
SiO_2	67.2	76.0	75.9
TiO_2	0.6	0.4	0.1
Al_2O_3	14.5	11.0	12.3
Fe_2O_3	1.3	--	--
FeO	2.3	2.0	0.8
MnO	0.049	--	tr
MgO	1.8	0.4	0.1
CaO	3.9	1.7	0.7
Na_2O	3.6	3.8	3.2
K_2O	2.5	4.2	5.2
H_2O^+	0.3	--	--
	97.749	99.5	98.3

Trace Elements (ppm)	S78-116	Rep., N. Wash. dist.	Threshold[7] Pac. NW
Ag	0.3	0.7	-0.1
Cu	95	40	50
Mo	3	3	-1
Pb	4	18	20
Zn	55	12	60

[1]NW 1/4 sec. 29, T. 3 N., R 5 E.; [2]Schriener, 1979, p. 53; total iron reported as FeO; [3]Erikson, 1969, p. 2224: total iron reported as FeO; [4]includes perthite; [5]sphene, zircon, apatite; [6]chlorite, clay; [7]Field and others, 1974, p. 17.

Hopson, and Waters, 1963; Sillitoe, 1973; Hopson and others, 1975). Evidence for such a relationship may be found in the close proximity and similar chemical trends in rocks of the Cascade Range.

The Silver Star stock contains xenoliths of the surrounding volcanic rocks of the East Fork formation, and the intrusion has imposed a contact metamorphic hornfels upon the basal flows of the Skamania formation. Thus, the stock is younger than these units. However, the upper flows of the Skamania formation exhibit little alteration in comparison with the basal flows. Consequently, there may exist a co-magmatic relationship between the upper part of the Skamania formation and the Silver Star stock. Limited evidence for this relationship is presented in this report. Further detailed examination of the chemistry of the upper Skamania formation would be necessary to confirm or deny this possible relationship.

The major oxide chemical trends for ten samples from the southern Washougal district are plotted on partial Harker variation diagrams (Figure 4). With the exception of the vesicular porphyritic quartz diorite, there is a general increase in K_2O and a decrease in MgO, CaO, Al_2O_3, and FeO with increased silica content for the rocks of the district. In addition, when their major oxide data are plotted on ternary AFM and NKC diagrams (Figure 5), systematic variations in chemistry similar to the calc-alkaline trend of the Southern California Batholith (Nockolds and Allen, 1953) are exhibited.

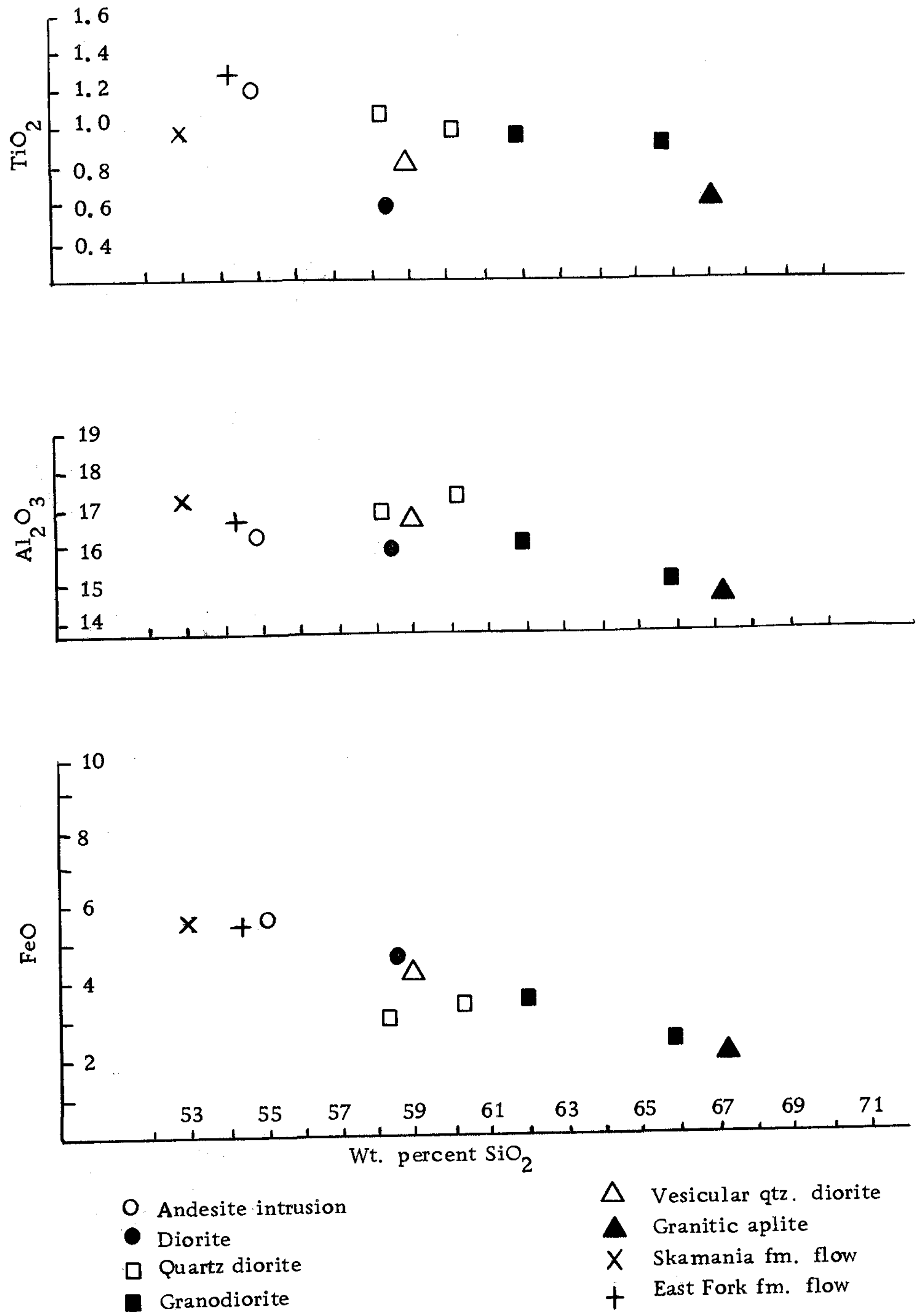

Figure 4. Partial Harker variation diagrams for volcanic and plutonic rocks of the southern Washougal mining district.

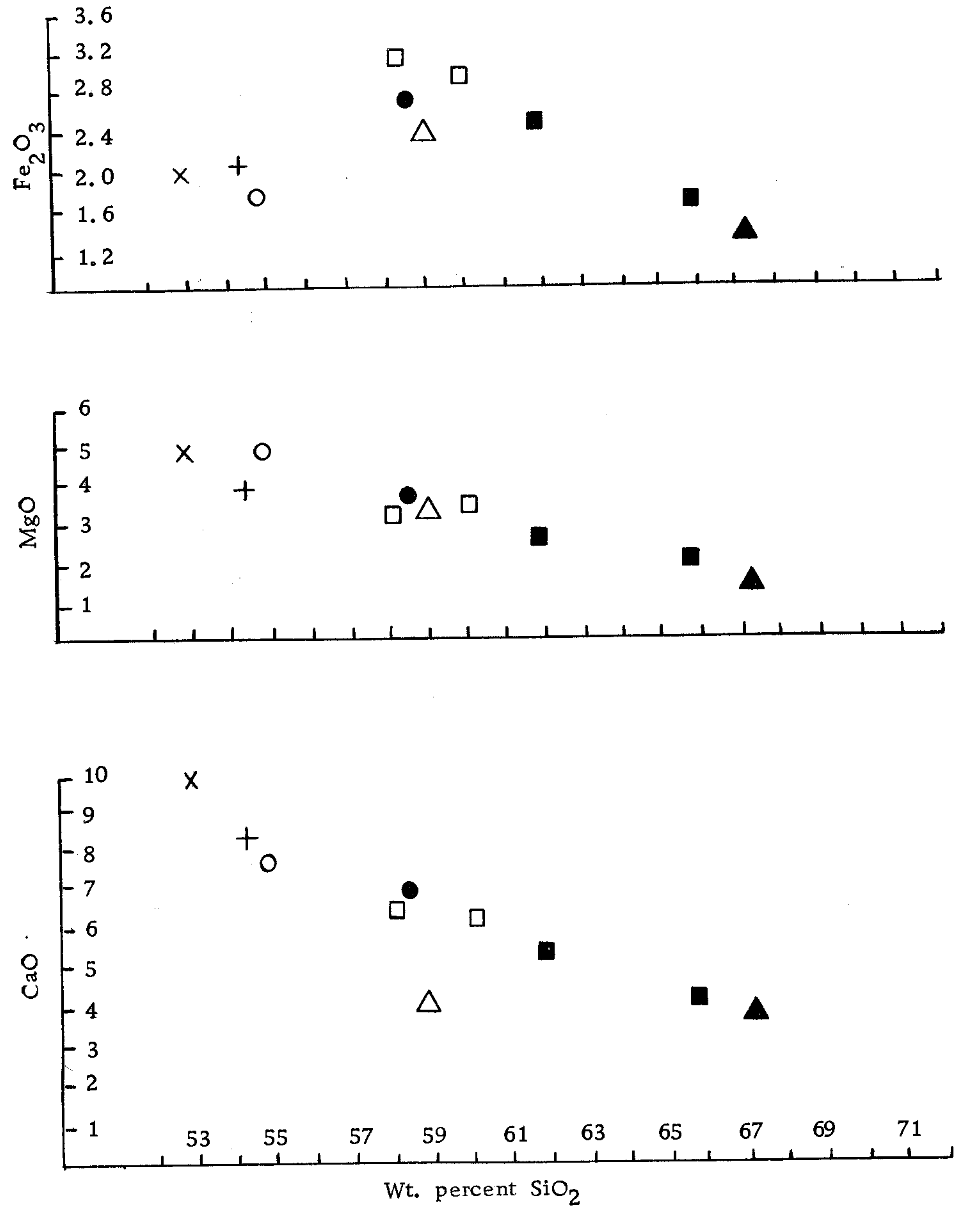

Figure 4. (Continued)

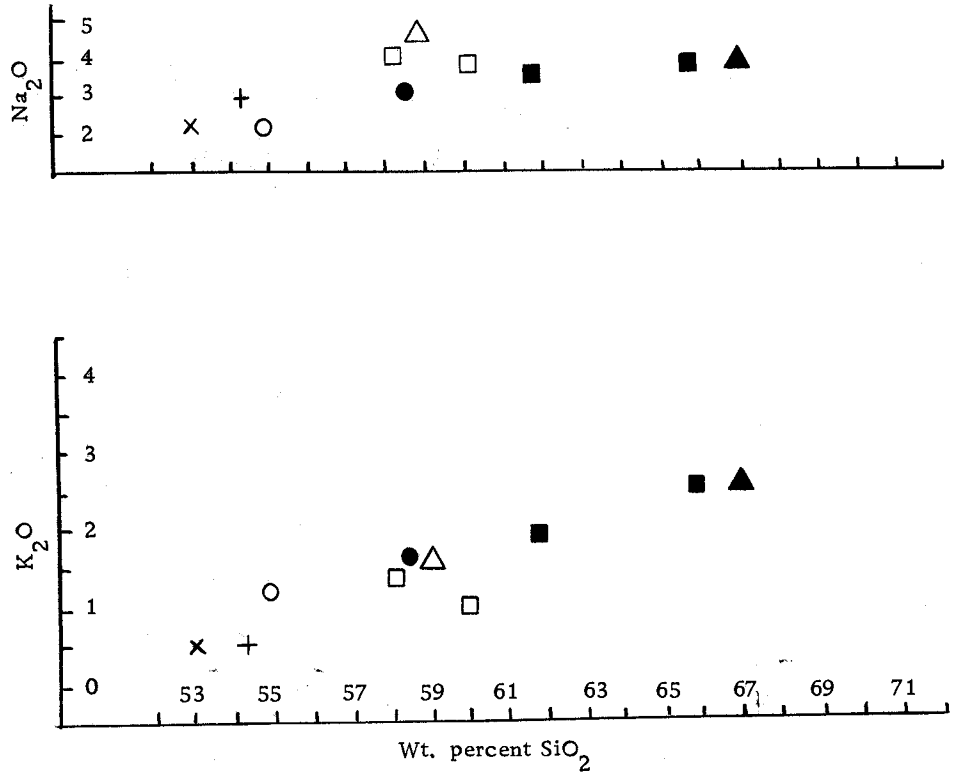

Figure 4. (Continued)

Such variations are thought to be indicative of a rock suite derived from a single differentiated magma. The diagrams show a general enrichment in alkalis versus iron and magnesium and in K_2O versus CaO + Na_2O with increased silica content. The vesicular porphyritic quartz diorite, however, represents a brief reversal in the general trend. Cater (1969) has noted a similar lack of correlation between the order of intrusion and the trend of differentiation in the Cloudy Pass Batholith in the northern Cascades of Washington. He states:

> No intrinsic reason exists why earlier, more mafic maga or later, more mafic differentiates could not have been squeezed from the depths of the magma chamber... (Cater, 1969, p. 42-43).

The flow sample from the unaltered part of the Skamania formation fits chemically at the mafic end of the calc-alkaline trend in the AFM and NKC diagrams of Figure 5. This may suggest a co-magmatic relationship in which the flow rock is the relatively undifferentiated surface expression of magmatic intrusion at depth.

The alkali-lime index (Peacock index) for the igneous rocks of the Washougal district is approximately 60.8 percent, as determined by the weight percentages of CaO: Na_2O plus K_2O at unity versus percentage SiO_2. Rocks of the calc-alkaline trend plot between 55 and 61 percent. Thus the igneous rocks of the district represent a highly calcic calc-alkaline sequence.

The modal and normative mineral calculations provide a

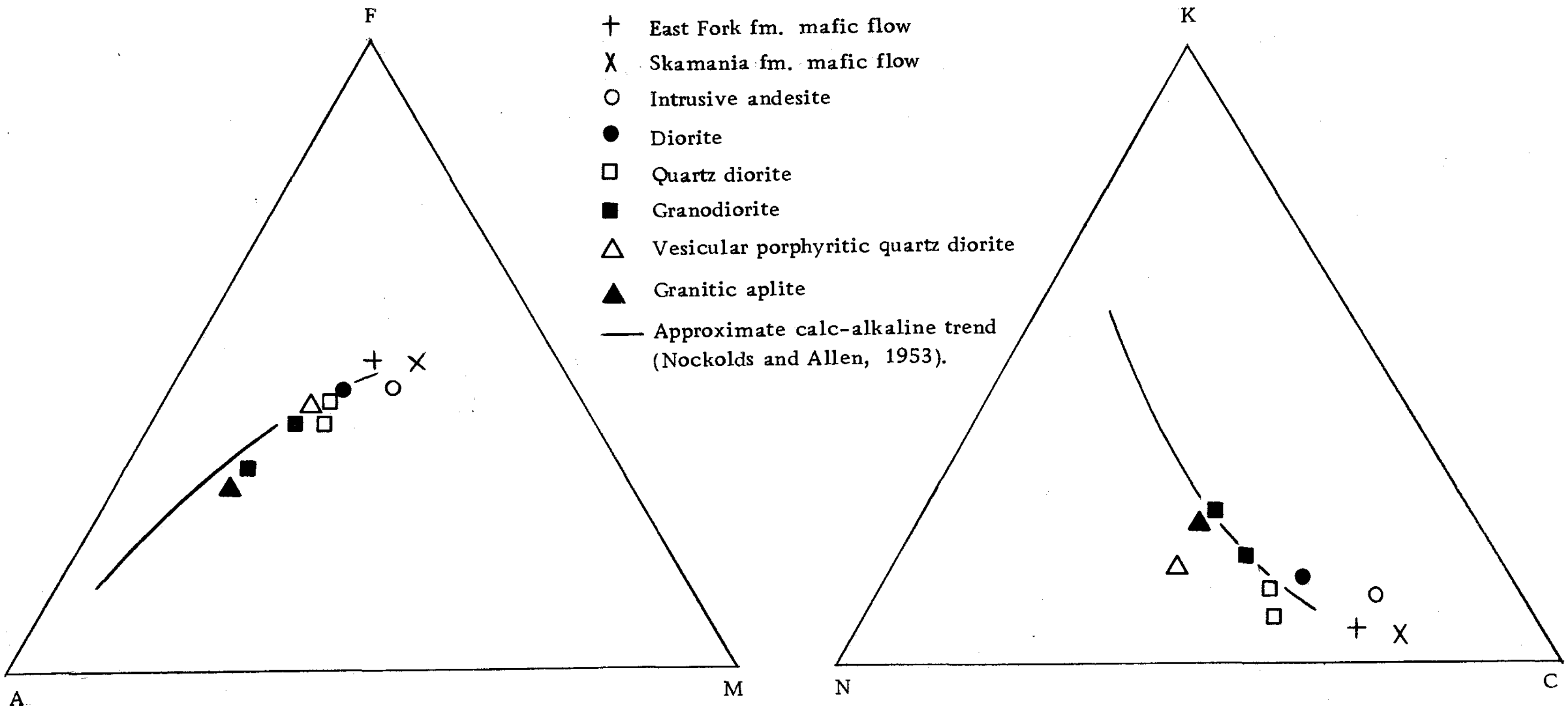

Figure 5. AFM and NKC diagrams for igneous rocks of the southern Washougal Mining District. $A = Na_2O + K_2O$; $F = FeO + Fe_2O_3$; $M = MgO$; $N = Na_2O$; $K = K_2O$; $C = CaO$.

qualitative means of comparing the rocks of the Washougal district to those of an ideal intrusion that has cooled very slowly. These analyses are plotted on partial ternary diagrams in Figure 6. The upper diagram in Figure 6 is the modal analyses for rocks of the district plotted within the IUGS classification system for plutonic rocks. The lower diagram represents the normative analyses plotted on a Q, Or, Ab plus An diagram, which is the chemical analog of the IUGS system. It may be seen that the rocks of the district chemically do not exhibit the enrichment in orthoclase that is shown by the modal analyses. In addition, the normative orthoclase content of the quartz diorites does not appear in the modal analyses, and thus the potash is either contained in solid solution with plagioclase feldspar, or in alteration minerals such as clays or sericite. Such divergences from the ideal composition, if not caused by alteration, are indicative of shallow-level intrusions that cooled relatively quickly.

The development of comparatively potassium-poor intrusive stocks has been associated with porphyry copper systems in island arcs (Titley, 1975; Field and others, 1975; Kesler and others, 1975; Kesler and others, 1977). The rocks of the southern Silver Star stock exhibit a close affinity to the "granodiorite trend" of Kesler and others (1975), and documented by Field and others (1975). Such sequences are suggested to represent rocks derived from a source more primitive than their continental counterparts in porphyry copper

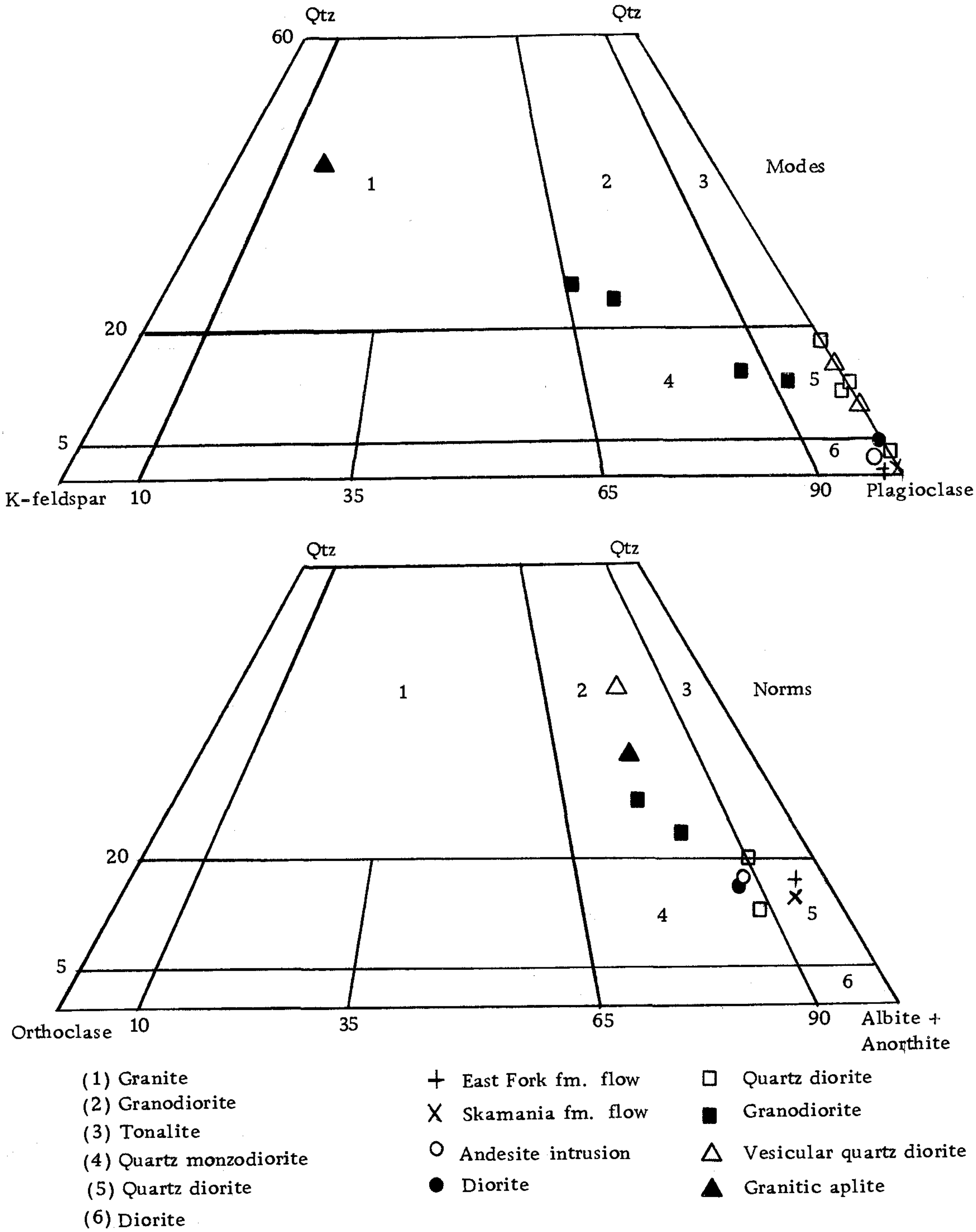

Figure 6. Modal and normative composition trends from the southern Washougal mining district, rock names for the numbered fields are from the IUGS classification.

systems. The magma source is mantle material, with little or no contamination from cratonic material, subducted oceanic lithosphere, or volcaniclastic sediments. A similar conclusion for plutonism in the Cascade Range of Oregon is presented by McBirney and White (1977). It would appear likely that the intrusive and volcanic rocks of the Washougal district are also derived from primitive source material.

STRUCTURE

The western flank of the southern Cascade Range of Washington is characterized by a series of broad en echelon doubly-plunging folds (Zeitz and others, 1971). According to Hammond and others (1977), a northwest-trending syncline abuts against the southeast margin of the Silver Star stock. However, evidence for such a structure was not found in the district. Bedding plane attitudes of volcaniclastic units of the East Fork formation strike roughly perpendicular to the axis of the syncline proposed by Hammond and others (1977). In addition, the overlying Skamania formation is nearly flat-lying in the area of study. It is possible that too small an area in the Washougal District was studied to provide indications of such a large-scale feature. Thus, more stratigraphic and structural information from the surrounding terrain are needed to confirm or deny the existence of such a fold.

Locally, the Washougal District exhibits numerous small, high angle faults of uncertain displacement. The lack of continuous exposures and recognizable marker horizons in the volcanic country rock would render any large-scale estimate of relative movement speculative at best.

Two separate shear zones are located within the Silver Star stock (Plate 1). The zones trend in a northeasterly direction and are nearly vertical. Although the extent and direction of movement along them is not known, the zones are the loci of intense hydrothermal alteration and rock cataclasis. The zones are four to eight meters wide, and are bounded by sharp contacts with competent, relatively unaltered granodiorite. Alteration products in the shear zones include sericite and thin (less than 0.25 mm wide) veinlets of tourmaline.

Host rocks of the Washougal District are fractured in a relatively systematic manner. A pole to plane Schmidt equal area projection (lower hemisphere) of 114 joint attitudes from the three major rock units of the district is given in Figure 7. There is good agreement between the patterns of each of the rock units, and thus they were combined to form a single comprehensive diagram. Two dominant systems among the joints are suggested from the plotted data. The first is composed of a northeast-trending joint set striking N. 15° E. to N. 53° E., and dipping vertically. The second strikes from N. 43° W. to N. 72° W., and is also nearly vertical.

Mineralized quartz veins in the southern part of the Washougal District exhibit roughly sub-parallel trends. The strikes of these veins varies from N. 45° W. to N. 76° W., and dips vary between 60° S. and 75° N. The general trend of these veins corresponds to the northwesterly joint set of the district, and is approximately normal to the north-south elongation of the Silver Star stock. In addition,

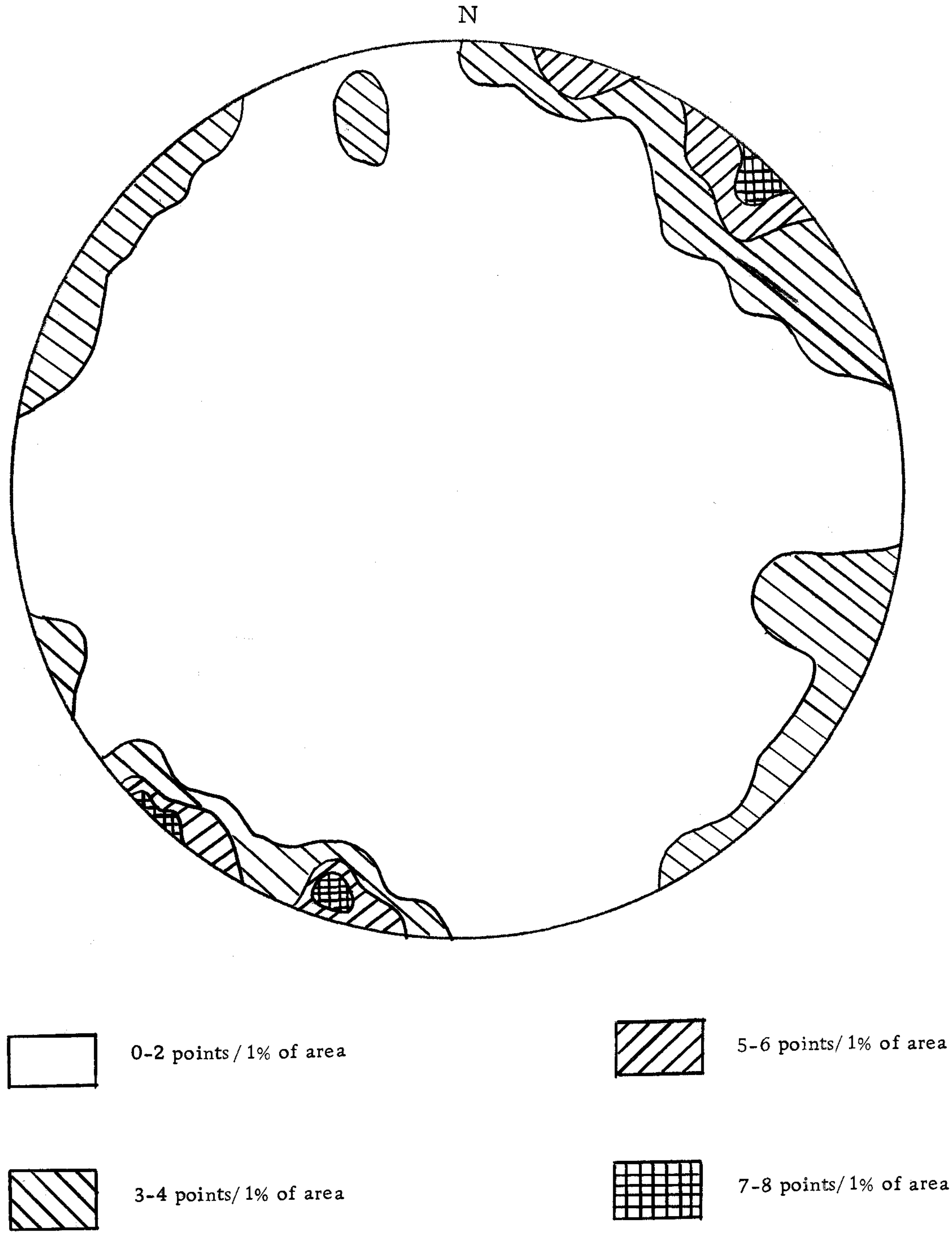

Figure 7. Pole to plane Schmidt equal area projection (lower hemisphere) of 114 joint attitudes in the southern part of the Washougal District.

the quartz veins extend from within the stock out into the volcanic country rocks without significant variations in attitudes (Heath, 1966).

Grant (1969) has suggested that the veins were originally tensional openings, formed by stresses after emplacement and crystallization of the Silver Star magma. These openings later became channelways for ascending hydrothermal fluids. Burnham (in press) suggests that the development of fractures in the apical parts of a cooling stock will be strongly influenced by the regional stress field (tectonic setting).

The close agreement between the joint patterns in the Silver Star stock and the surrounding country rock suggests that a co-genetic relationship exists between them. Locally, stress was apparently applied after the emplacement of the stock and during the subsequent hydrothermal activity associated with the cooling intrusive. In addition, the regionally widespread preferred orientation of mineralized vein systems documented by Grant (1969) suggests that the stress was present over much of the Cascade Range of Washington during the periods of intrusive activity.

ECONOMIC GEOLOGY

Discoveries of copper and gold during the late 1890's brought scores of prospectors into the southern part of Skamania County, Washington. By the turn of the century, five mining districts had been established. In 1930 they were combined to form the Washougal Mining District. Most of the activity ceased, however, after devastating forest fires in 1902 and 1929. A few properties in the southern part of the district have undergone modest development since that time, but at present all are inactive. The total recorded mineral production from the southern part of the Washougal District, from 1903 to 1974, amounted to $394, derived from copper and silver. The entire district has produced only $573 in that time.

Mineral Deposits

The principal type of metallic mineralization in the southern part of the Washougal District occurs as quartz-sulfide veins. The most persistent mineralization appears in the Last Chance, Skamania, and Maybee Mines. All of these claims are inactive, and the adits of the Maybee and Skamania Mines have caved. The adit of the Last Chance Mine is open. However, it is flooded, and it was deemed inadvisable to attempt to enter the mine. Thus, descriptions of the veins are taken from Howe (1938), Chichester (1953), Appling (1955), and Heath (1966). It should be noted that the locations of the Skamania and Last Chance Mines are reversed on the Bridal Veil 15-minute quadrangle map (the base map for Plate 1). Thus, the Last Chance Mine is located in the southeast quarter of sec. 29, and the Skamania Mine is located in the southwest quarter of sec. 21, T. 3 N., R. 5 E.

The quartz-sulfide veins in the southern part of the Washougal District are found in both the Silver Star stock and the adjacent East Fork (Ohanapecosh) volcanics. The veins are relatively continuous and tend to be isolated from one another. They exhibit little branching or divergence while within the stock, and vein widths may vary from a few centimeters to several meters. The veins deteriorate into fine breccia as they enter the volcanic host (Heath, 1966). Most of the veins trend northwest, which is approximately perpendicular to the elongation of the Silver Star stock. The veins dip steeply, varying from 60° S. to 75° N.

Fault movements do not appear to have been important in the formation of the veins. Rather, they have undergone repeated episodes of dilation, resulting in brecciation and numerous vugs and cavities. Slickensides are of limited extent and are caused by strike-slip displacement of a few centimeters. They have been described by Howe (1938) in one vein deposit in the center of sec. 21, T. 3 N., R. 5 E.

The quartz gangue in the veins is clear to sugary-white in color, and forms thin subparallel bands usually less than three millimeters wide. Comb and drusy textures are commonly developed, as are vugs up to two millimeters in diameter. Trace amounts of amythestine quartz are also present in the veins.

The vein quartz may contain fluid inclusions of the primary, pseudosecondary, or secondary type, as classified by Roedder (1972). They are small, averaging approximately 0.02 mm in size, and are usually very irregular in shape. They contain a fluid phase, a gaseous bubble, and generally one cubic daughter product that is probably halite. The gas bubbles rarely exhibit Brownian motion.

The principal minerals of interest in the veins of the district are bornite, chalcopyrite, galena, and sphalerite. They occur as small disseminated blebs and stringers in the vein quartz, and commonly are associated with and partially replace altered country rock. Bornite is the most abundant sulfide of copper found on the dumps of the Last Chance and Skamania Mines. Pyrite is scattered and not abundant in any of the vein deposits.

Minerals formed by supergene oxidation are very common, as the intensely fractured and brecciated brittle host rocks allow ready access for the oxygenated ground water.

Chalcocite and covellite are formed as coatings or replacements of primary copper sulfides. Malachite, chrysocolla, and minor azurite are ubiquitously present. Traces of brochantite (Howe, 1938) and descloizite (Heath, 1966) are reported in the Last Chance vein.

Samples of the Last Chance vein collected by Chichester (1953) for the U.S. Bureau of Mines indicated values of 2.75 percent copper and 0.71 ounces per ton silver over the length of the eastern adit, and over an average vein width of four feet. Sampling conducted by Appling (1955), also for the U.S. Bureau of Mines, indicated values for the eastern adit of the Skamania Mine of 3.14 percent copper and 2.44 ounces of silver per ton, with traces of gold, for the length of the adit and over an average vein width of 3.5 feet (Heath, 1966; Moen, 1977).

Heath (1966) has reported a possible crude zonation to primary sulfide minerals of the Washougal District. Deposits in and near the Silver Star stock show greater concentrations of copper-bearing minerals relative to those of lead and zinc. The reverse is true for veins more distant from the intrusive contact. Such zonations are common in porphyry copper systems as described by Lowell and Guilbert (1970) and Rose (1970) and many others.

Alteration

The alteration assemblages associated with the Silver Star stock are generally consistent with those described for porphyry copper systems (Creasey, 1966; Meyer and Hemley, 1967; Lowell and Guilbert, 1970; Rose, 1970, Guilbert and Lowell, 1974). These mineral assemblages are referred to as the potassic (potassium silicate), phyllic, argillic, and propylitic assemblage zones. The potassic and argillic zones are not present in the southern part of the Washougal District. In addition, evidence of contact metamorphism of the albite-epidote hornfels facies is found in rock samples from the southeast margin of the Silver Star stock (S78-50).

In the southern part of the Washougal District the propylitic assemblage is composed of the minerals chlorite, magnetite, epidote, quartz, albite, calcite, uralite, and traces of actinolite. Similarly, deuteric alteration, albite-epidote hornfels facies, and low grade greenschist facies are characterized by members of this same group of minerals.

Hartman (1973) concluded that alteration in Tertiary volcanic rocks of the central Washington Cascades was the result of hydrothermal alteration developed around igneous intrusions, rather than as a result of regional burial metamorphism. On the basis of ^{18}O data, Taylor (1971) suggested that much "deuteric" alteration in the western Cascades of Oregon was caused by meteoric-hydrothermal waters rather than H_2O released by a cooling intrusion. In the southern part of the Washougal District the propylitic alteration zone is developed around and within the Silver Star stock. Thus, the propylitic zone is probably formed as the result of hydrothermal activity associated with crystallization and cooling of the Silver Star stock. The approximate aerial extent of this zone is indicated on

Plate 1, and is referred to as the "contact aureole."

Chlorite and magnetite commonly occur together in the prophylitic zone, usually as replacements of primary ferromagnesian minerals. Chlorite forms anhedral felty masses where not pseudomorphic after primary minerals. In some instances, chlorite is one of several minerals that occur in orbicules in the sub-volcanic rocks southeast of the Silver Star stock (p. 38). Anhedral magnetite grains are usually less than 0.5 mm in diameter.

Epidote is found as an alteration product of plagioclase feldspar. It is also contained within veinlets crosscutting volcanic rocks of the district, or as part of the orbicular texture previously mentioned. It usually forms anhedral aggregates in either of these occurrences, with individual crystals less than 0.25 mm in diameter.

Uralite is a fibrous amphibole which forms as an alteration product of primary pyroxenes. Primary hornblende in the Silver Star stock is identified on the basis of simple boundaries with other mineral grains, and optical continuity. Uralite, however, occurs as fibrous, subparallel crystals crudely aligned along the former C crystallographic axis of the pyroxene. The fibers are very pale green, with slight pleochroism, and low to intermediate birefringence. The angle of extinction varies between 15 and 20 degrees. The characteristic amphibole cross-section was not found in these finely crystalline minerals.

Actinolite is present in thin veinlets less than one millimeter wide that crosscut volcanic rocks of the district. Where the veinlets intersect phenocrysts of pyroxene in the mafic flow rocks, the actinolite may extend into the phenocryst and replace it. These veinlets are relatively rare and were observed only in two thin sections from the volcanic rocks of the East Fork and Skamania formations of the district.

Albite and calcite are rare minerals in the propylitic assemblages of the district. Albite occurs as very fine-grained subhedral crystals in the groundmass of a hornfelsed volcaniclastic rock from the southeast margin of the Silver Star stock (S78-50a). In addition, traces of albite are present in rocks immediately adjacent to the mineralized veins of the district. Calcite is variably present as an alteration product of plagioclase feldspar.

The phyllic alteration assemblage is characterized by quartz, sericite, pyrite, and tourmaline. This assemblage is found only in restricted locations in the southern part of the Washougal District. Specifically, it is found in two shear zones from the southwestern part of the Silver Star stock, and in breccia pipes scattered through the area of study (Plate 1). In these two types of occurrences, alteration of the host rock is nearly complete, and few relict minerals of the original rock remain unaltered.

Quartz, lightly dusted with sericite, tends to form a finely crystalline mosaic in the matrix of the intrusive breccias. The outlines of the clasts are still present, but they are entirely replaced by a fine intergrowth of quartz and sericite. Thus, the relative percentages of quartz and sericite may vary considerably, dependent upon whether or not a particular sample is rich in matrix or clasts. One example of such relict textures was collected from the breccia pipe in the northeast quarter of sec. 28, T. 3 N., R. 5 E.

Pyrite is scattered in only trace amounts throughout zones characterized by the phyllic assemblage. It forms subhedral to euhedral crystals (cubes and pyritohedrons) up to one millimeter in diameter. In three thin sections taken from samples of the hydrothermal breccia pipes, the pyrite was invariably replaced by limonite.

The sporadic occurrence of pyrite in porphyry copper systems in the Pacific Northwest has been examined by Field and others (1974). They have indicated that an imperfectly developed pyrite halo is caused by (1) low initial concentration of iron in the plutonic host rocks, (2) conditions of high Eh-low pH, as indicated by hypogene iron oxides and sulfates, or (3) iron-deficient hydrothermal fluids. In the southern part of the Washougal District, iron is present in normal concentrations (3.6 to 7.5 percent) in the intrusive igneous rocks. In addition, sulfates are lacking in the area. The iron oxides could be hypogene in nature. However, their pseudomorphism after pyrite and their development in boxworks would seem to indicate a supergene origin.

Thus, it is inferred that the original hydrothermal fluids were iron-deficient.

Tourmaline occurs sporadically in one of the breccia pipes of the southern part of the district (NE 1/4 sec. 18, T. 3 N., R. 5 E.), and in the northernmost of the two shear zones in the Silver Star stock (NW 1/4 sec, 30, T. 3 N., R. 5 E.). The tourmaline in the shear zones forms thin veinlets less than 0.5 mm wide in altered granodiorite. In the intrusive breccia pipe, tourmaline is present in small vugs, as radiating acicular crystals, up to one centimeter in diameter.

Evidence of contact metamorphism of the albite-epidote hornfels facies is found in a thin section of sample S78-50b (NW 1/4 sec. 6, T. 2 N., R. 5 E.). The mineral assemblage includes biotite, magnetite, pyrite, epidote, and microcrystalline quartz and andesine (An_{36}).

Biotite forms fine-grained polycrystalline aggregates as an alteration product of primary clinopyroxenes. Biotite does not normally appear in any of the zones of propylitic alteration. It is reddish-brown to light tan in color, and is commonly associated with ragged, anhedral magnetite.

Pyrite appears in subhedral to anhedral crystals less than 0.5 mm in diameter scattered throughout the thin section. However, it comprises less than one percent of the rock.

Epidote occurs as anhedral crystals less than 0.25 mm in diameter, or as incrustations upon primary plagioclase feldspar.

Quartz and andesine form an anhedral microcrystalline mosaic in the interstices between primary minerals of the host granodiorite. They appear to have been formed by the recrystallization of interstitial minerals of the host rock. They average less than 0.25 mm in diameter.

Breccia Pipes

Breccias occurring as cylindrical pipes and elongate zones are commonly associated with hydrothermally mineralized systems. Such breccias have been described in the Cascade Range of Washington by Cater (1969); Grant (1969); Patton, Grant, and Cheney (1973); Field and others (1974); and Schriener (1979).

The southern part of the Washougal Mining District contains ten pipe-like and crudely ovoid shaped breccia zones. The breccias may be located within the Silver Star stock, or in the surrounding volcanic country rock. The outer margins of the breccia pipes in the district are usually covered by talus and (or) vegetation. Consequently, the shape and aerial extent of individual breccias are largely inferred on the basis of talus. In a few instances, the pipes stand as high as thirty-five meters above the adjacent topography. Especially prominent in the area is a close grouping of breccia pipes in the northeast quarter of sec. 28, T. 3 N., R. 5 E., known locally as

Chimney Rocks (Grauer, 1977).

Breccias in the southern part of the Washougal District are composed of fragmented wall rock suspended in a matrix of rock flour, finely crystalline quartz, and scattered sericite and pyrite. With one exception (NW 1/4 sec. 18, T. 3 N., R. 5 E.), tourmaline is not present in the breccias. The rock fragments, or clasts, in the breccias may be angular to subrounded in shape, and measure up to five centimeters in diameter. The clasts are usually completely replaced by sericite and quartz, having only a ghost-like outline of their former shape. In one instance, however, clasts in a breccia from Chimney Rocks were recognizable as bedded volcaniclastic siltstone.

The breccias have been the loci for intense hydrothermal alteration, and contain minerals characteristic of the phyllic alteration zone. Quartz is present as a finely crystalline mosaic in the matrix of the breccias. In addition, it may be present in vugs as crystals measuring up to one centimeter in length. Sericite is scattered throughout the matrix, and commonly replaces entire clasts in the breccias. Pyrite occurs sporadically as euhedral crystals averaging one millimeter in diameter. It is usually replaced by limonite.

One breccia zone contains minerals indicative of the propylitic alteration assemblage (SW 1/4 sec. 33, T. 3 N., R. 5 E.). The minerals include chlorite, epidote, and magnetite. In addition, minor amounts of pyrite are present. The breccia contains angular to subangular clasts up to one centimeter in diameter suspended in a matrix of anhedral quartz and chlorite. The clasts are readily recognizable as fragments of a porphyritic mafic flow rock. Epidote preferentially replaces some clasts, obliterating their primary textures.

The breccia pipes in the northern part of the Washougal District have been examined by Schriener (1979). There are significant differences between the breccia pipes in the north and south parts of the district. Moreover, Schriener (1979) has described two texturally different types of breccias, that appear to be gradational with one another. One variety is a "rubble-rich" breccia that contains angular to lath-like clasts in sub-parallel alignment, cemented in a matrix of hydrothermal tourmaline, quartz, and amphibole. The second type of breccia is the "matrix-rich" variety, which is characterized by fragments of wall rock suspended in a matrix of finely granular quartz, tourmaline, and rock flour. This breccia type exhibits a wide variation in clast sizes and shapes. Clasts range from one millimeter to as much as fifty centimeters in diameter, and from angular to subrounded in shape. The breccia pipes of the southern part of the Washougal District are of the matrix-rich variety, and differ only in their lack of tourmaline in the breccia matrix.

Current theories regarding the development of breccia pipes include: (1) fluidization processes (Reynolds, 1954; Bryant, 1968;

Phillips, 1973, 1974; Gilmour, 1977); (2) solution stoping of overlying rock (Bryner, 1968; Sillitoe and Sawkins, 1971); (3) roof slumpage caused by episodic magma pulsation (Gates, 1959; Perry, 1961); and (4) exsolution and migration of volatile fluids (Norton and Cathles, 1973; Phillips, 1973, 1974).

Briefly, the fluidization phenomenon occurs as a fluid (liquid or gas) flows rapidly or is agitated sufficiently to incorporate rock particles into traction or suspension. In hydrothermal systems, the conduit through which the fluid is moving may be vented to the surface, producing a pressure gradient sufficient to cause rapid movement. This process produces much attrition of the rock fragments and yields rock flour and abraded clasts. Deposition of suspended material occurs as flow rates drop below those necessary to carry the rock particles. This may be caused by sealing of the surface vent of the hydrothermal system, or choking of the conduit.

Solution stoping, or chemical brecciation, is a process by which corrosive hydrothermal fluids locally dissolve wall and roof rock and create a void. When the void reaches a critical volume, the walls and roof collapse to form a "hydrothermal collapse breccia" (Bryner, 1968; Sillitoe and Sawkins, 1971).

Breccias formed as the result of fluctuations in magma pressure have been suggested by Perry (1961) and Gates (1959). Spasms of such magmatic pressures cause breakage and removal of fragments

fragments from the chilled rind of an intrusion. Repetition of such magmatic pulsations result in expansion of the breccia zones, which act as low-pressure centers for the concentration of residual fluids during the later stages of magma crystallization and hydrothermal activity.

Finally, the exsolution of volatile-rich hydrous phases from a crystallizing magma has been examined by Norton and Cathles (1973), and Phillips (1973, 1974). Their models are similar in that they envision the exsolution of hydrous phases within the cooled outer rind of a magmatic intrusion. In the model of Norton and Cathles (1973), however, chemical reactions cannot occur between the trapped fluids and the igneous body. Release of the fluids, and thus the formation of breccia pipes, is dependent upon the development of tensional cracks formed in the intrusion and the overlying country rocks as it cools. In the model proposed by Phillips (1973, 1974), the volatile components in the cooling and crystallizing magma would concentrate in the residual liquid until their total vapor pressure exceeded the confining pressure of the intrusion. This condition would result in rapid vesiculation (resurgent boiling) and expansion of the volatile phase. The rapid accumulation of these volatiles, as bubbles, would cause extensive fracturing and microbrecciation of the cooled outer shell of the intrusive body. Such fluids would subsequently migrate upward to regions of lower pressure (Phillips, 1973, 1974).

Origin of the Washougal Breccia Pipes

Hypotheses attempting to explain the development of breccia pipes in the Washougal District must account for: (1) the formation of matrix-rich and rubble-rich varieties of breccia; (2) the lack of tourmaline in the breccias of the southern part of the district; (3) the spatial association of the breccias with zones of structural weakness; (4) the lithology, angularity, and alteration of the clasts; and (5) the abundance of rock flour in the matrix of the breccias.

The distribution of tourmaline is of possible importance in determining the genesis of the breccias of the district. At the porphyry copper depost at El Salvador, Chile, a vertical zonation of tourmaline is present (Gustafson and Hunt, 1975). It is rare in veins at the lower levels of the mine, and disseminated rosettes of tourmaline are lacking. In contrast, tourmaline is widespread and abundant in the upper levels of the mine. Moreover, the tourmaline appears to be closely associated in time with the sulfide mineralization. By analogy, it may be inferred that the tourmaline-rich breccia pipes in the northern part of the Washougal District represent shallower levels of exposure than do the quartz-rich breccias in the southern part of the district. In addition, the tenor of sulfide mineralization is relatively higher in the breccias of the northern part of the area.

It must be noted that the inferred vertical zonation of tourmaline is not actually observed in the southern part of the Washougal District. In addition, the mineralized breccias in the northern part of the district are exposed at elevations of approximately 1600 feet, and are contained within the granodiorite phase of the Silver Star stock. The elevations of the quartz vein deposits on the southeast margin of the stock are also approximately 1600 feet. Matrix-rich breccias on Hemlock Ridge (Schriener, 1979, p. 68) crop out at elevations of approximately 3000 feet, which is nearly equal to that of the Chimney Rocks breccias in the southern part of the district. Thus, the interpretation that follows may be subject to some question with regard to the relative levels of exposure in the breccia pipes of the northern and southern parts of the district.

The cooling and crystallization of an H_2O undersaturated magmatic intrusion results in the progressive concentration (exsolution) of water-rich volatiles. Such magmatic waters, being less dense than the surrounding crystals and magma, would tend to migrate upward and accumulate beneath the crystalline carapace of the intrusion (Burnham, 1967; in press). This zone of water accumulation would eventually become saturated with respect to H_2O.

In the model suggested by Norton and Cathles (1973), the outer rind of the intrusion would, in time, develop tensional fractures, caused by contraction of the pluton with cooling and further cyrstallization. On the other hand, Burnham (in press) suggests that the vapor pressure of the hydrous phase would eventually exceed the pressures containing the intrusion (lithostatic load plus tensile strength of the cooled rind). These "vapor" overpressures would cause lateral extension of the carapace and consequent tensional fracturing of this brittle rind, thus allowing the escape of volatiles. Phillips (1973, 1974) has suggested that such vapor overpressures developed beneath the carapace would result in rapid vesiculation and resurgent boiling of the hydrous fluids. These fluids would be active both chemically and mechanically, causing hydraulic fracturing and intense microbrecciation of overlying brittle rock, allowing upward migration of the fluids.

Burnham (in press) has noted that fractures in the rocks overlying the vapor-saturated zone of the intrusion would tend to be steep, "because expansion of the system occurs in the direction of least principal stress." The orientation of the fractures would be influenced by the regional stress fields (tectonic setting). Grant (1969) suggested regional structures, or "deformation zones" were responsible for the localization of mineral deposits in many areas of the Cascade Range of Washington. It is suggested that such regional influence was present during the mineralization of the Silver Star stock.

In particular, breccia pipes in the southern part of the Washougal Mining District commonly trend subparallel to the strike of mineralized veins on the southeast margin of the Silver Star stock. An examination of Plate 1 indicates a reasonably good alignment between the vein of the Skamania Mine (NW 1/4 sec. 28, T. 3 N., R. 5 E.) and the Chimney Rocks breccia pipes (NE 1/4 sec. 28, T. 3 N., R. 5 E.). It is suggested that the quartz veins functioned as channelways for ascending hydrothermal fluids that formed the breccia pipes.

As noted by Phillips (1973, 1974), rapid vesiculation and resurgent boiling of hydrothermal fluids results in the intense hydraulic fracturing and microbrecciation of brittle host rocks. The elevation at which boiling will occur in a "column" of hydrothermal fluids is dependent upon the temperature of the fluids and their vapor pressure. Where vapor pressure exceeds total confining pressure, boiling will occur (Burnham, 1967). Thus, the boiling of fluids is not restricted to the zone of water saturation beneath the rind of a cooling stock, but also may occur at any depth to which the fluids have access that meets the proper pressure-temperature conditions.

In the southern part of the Washougal District it appears that boiling of the hydrothermal fluids occurred at some elevation above the intrusive Silver Star stock, within the overlying volcanic and volcaniclastic rocks. This is indicated by the large amounts of rock flour, and the variable size and shapes of clasts contained in these breccias. In addition, the boiling fluids reacted chemically with the breccias, and altered them significantly to an assemblage

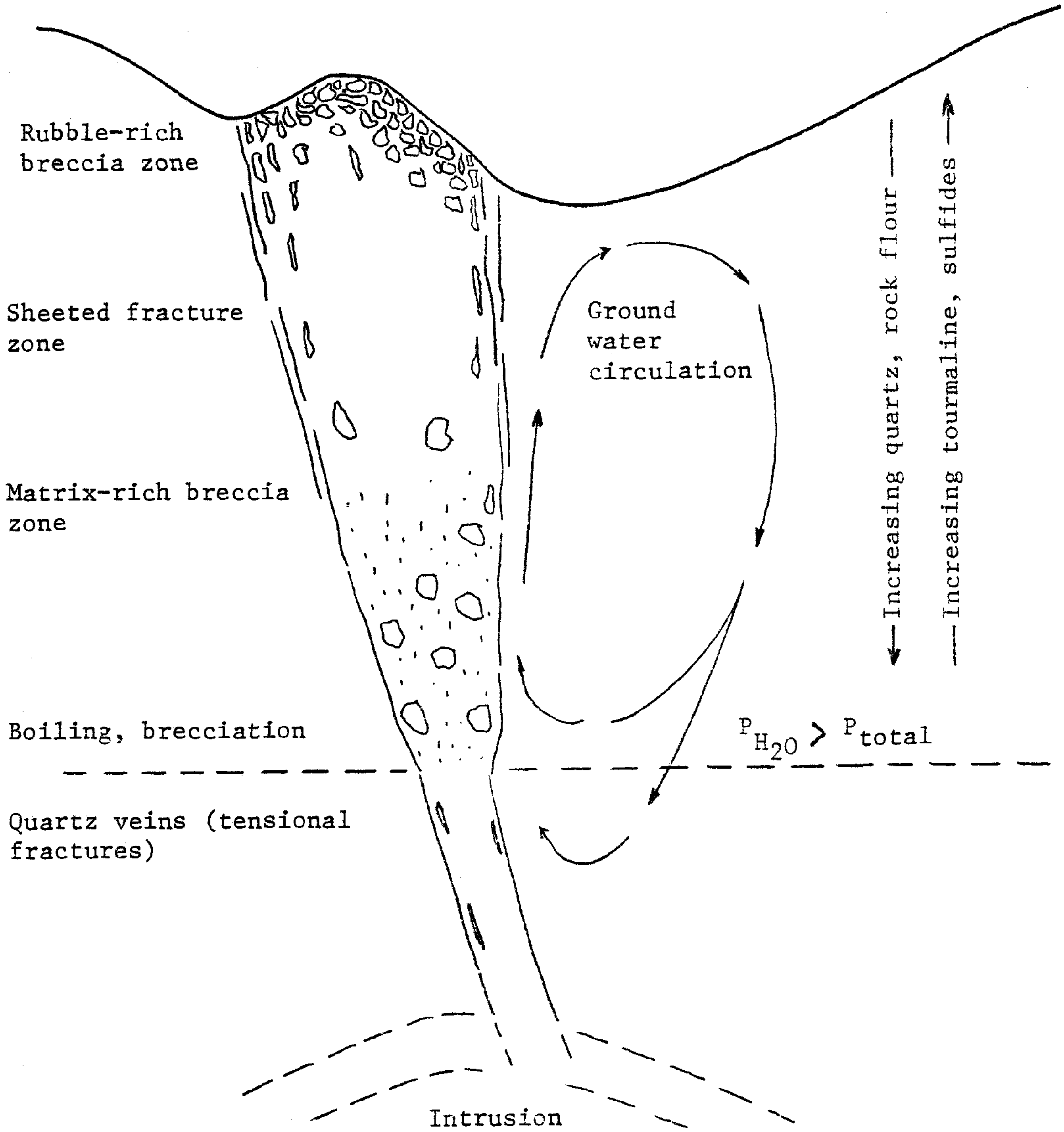

Figure 8. Cartoon indicating possible morphology of breccia pipe systems in the southern part of the Washougal Mining District.

predominated by quartz and sericite.

This concept is depicted diagrammatically in Figure 8. It is suggested that the tensional fractures developed in the cooled rind of the Silver Star stock are the result of (1) contraction of the pluton, as envisioned by Norton and Cathles (1973), or (2) regional stresses applied to the stock, as suggested by Grant (1969). If vesiculation and microbrecciation occurred within an intrusive body, clasts of the cooled rind of that body would be included in the breccias. Such is not the case in the breccias of the southern part of the Washougal District, which contain clasts from nearby wall rock.

Another important consequence of the hydraulic fracturing and microbrecciation associated with boiling would be an increase in the permeability of the rocks. The upward migration of hot magmatic fluids might then initiate extensive convective circulation and then draw large amounts of meteoric ground water into the system (Phillips, 1973).

The influx of the ground waters, as postulated by Taylor (1971, 1974), and the adiabatic expansion and cooling of the hydrothermal fluids would thus lower the temperature of the fluids. This reduction in temperature to values below the boiling point of the fluids would lead to decreased agitation and ebullition, and consequent diminished hydrofracturing and microbrecciation. Thus, the amount of rock flour and the abrasion of clasts would tend to decrease upward in the breccia pipes.

Breccias in the northern part of the Washougal District are commonly of the rubble-rich variety (Schriener, 1979). The matrix is predominantly tourmaline, and rock flour is conspicuously absent. Clasts are angular to lath-shaped, and also exhibit replacement textures with tourmaline. Norton and Cathles (1973) have noted that the apexes of breccia pipes are characterized by decreasing numbers of breccia fragments and an increase in sheet fracturing. Sillitoe and Sawkins (1971) made the same observation in their examination of Chilean breccia pipes, and further noted that tabular fragments present in the upper parts of the breccias had undergone variable amounts of rotation from their original positions in the fractured wall. Thus, the rounded clasts indicative of deeper elevations in the breccia pipes are gradually replaced by lath-shaped clasts that spalled inward from the walls of the higher parts of the pipes.

Schriener (1979) has described clasts in the rubble-rich breccias of the northern part of the Washougal District that are partly to completely altered to an assemblage of quartz, sericite, and clay, with tourmaline, iron oxides, amphibole, and sulfides. Thus, the ascending fluids were sufficiently chemically active to alter the clasts of wall-rock and to deposit this mineral assemblage. The fluids were mechanically capable of moving the fragments only a short distance from the walls of the pipe, however. Sillitoe and Sawkins (1971) have noted that the tabular clasts in some Chilean breccia pipes do not exhibit evidence of extensive vertical movement.

The upward termination of a breccia pipe is not exposed in the Washougal Mining District. Consequently, the models of Sillitoe and Sawkins (1971) and Norton and Cathles (1973) are suggested to apply to the district. In these models, the upper parts of the pipes are characterized by "shatter" or "crackle" breccias, in which the country rock has been fractured but not displaced. Displacement of clasts near the base of the shatter breccia zones is accomplished by means of solution stoping (Sawkins, 1969), a process by which clasts are removed from the wall and roof of the pipe by collapse into a void developed by the chemical action of the hydrothermal fluids.

The hydrothermal activity associated with the formation of breccia pipes tends to be episodic in character. Burnham (in press) suggests that as cooling of the intrusive stock below a breccia pipe continues, the crystalline outer rind of the stock would retreat to greater depths. Fractures would become sealed by the precipitation of minerals, chiefly quartz. Thus, the accumulation of hydrous fluids under the cooled rind would re-commence and possibly renew the cycle. This downward retreat of the breccia pipe hydrothermal system would be expressed as a collapse of the vertical mineralogical and textural zonation shown in Figure 8.

For example, sample S78-125, from the Black Jack prospect in the northern part of the Washougal District, exhibits a concentric zonal arrangement of quartz and tourmaline euhedra. Quartz crystal contain two zones - a clear central core surrounded by a milky white sheath. Tourmaline is formed as radiating acicular crystal aggregates between the quartz crystals, and needles of tourmaline may be seen penetrating both zones in the quartz from the outside. It is inferred that such zones in the quartz, with peripheral tourmaline represent episodic deposition and gradual collapse of the vertical mineral zonation in the breccia pipes of the district.

A corollary to the model proposed for the formation of breccia pipes in the district may be found in the vesicular porphyritic quartz diorite phase of the Silver Star stock. This phase exhibits vesicles, which may be taken as evidence of saturation in volatiles as proposed by Phillips (1973, 1974) and Burnham (in press). In addition, this vesicular phase contains numerous xenoliths of the surrounding country rock, and has anomalously high concentrations of copper (390 ppm). Schriener (1979) has reported a spatial association between quartz diorite porphyry (containing 670 ppm copper) and the Miners Queen copper deposit. Thus, it may be suggested that the vesicular porphyritic quartz diorite forms the "root zone" of mineralized breccia pipes in the Washougal District. Elsewhere, such mineralized vesicular intrusive phases have been reported at the Bingham porphyry copper deposit (Wilson, 1978), and in the Yeoval copper prospect in Australia (Ambler, 1979).

Trace Elements

The concentrations of trace elements (copper, silver, molybdenum, lead, and zinc) for rock chip, stream sediment, and mine waste dump samples are listed in Table 10. In addition, the threshold values for the Pacific Northwest, the northern part of the Washougal District, and the southern part of the district are given in Table 11. A threshold value is defined as the upper limit of the background concentration of a trace element (Levinson, 1974). Where a group of samples represent one distinct population of geochemical data, the threshold value of a trace element may be taken as the mean value plus two standard deviations (Peters, 1978). This is the procedure used to calculate the values for the southern part of the Washougal District listed in Table 11.

The threshold values for stream sediment samples in the southern part of the district are calculated on the basis of three of the four samples. These are S78-83, S78-85, and S78-96. Sample S78-84 is excluded because it represents a sample known to be anomalously mineralized. Levinson (1974, p. 213) indicates that in the procedure used to establish geochemical background concentrations of trace elements for an area, mineralized samples should be excluded.

Table 10. Trace element data for rock chip, stream sediment, and mine waste samples from the southern Washougal District.

Specimen	rock type	Ag	Cu	Mo	Pb	Zn
S78-1	volcaniclastic	0.5	120	-1	17	75
S78-5	intrusive	0.7	130	2	25	75
S78-9	breccia pipe	0.3	40	3	20	20
S78-22	volcaniclastic	0.6	100	1	12	60
S78-29	breccia pipe	0.3	50	4	15	16
S78-30	mafic flow	0.4	120	1	10	50
S78-70	intrusive	0.4	50	2	20	65
S78-73a	mafic flow	0.6	130	-1	10	30
S78-73b	mafic flow	0.3	165	2	30	40
S78-81b	intrusive	0.3	390	2	25	60
S78-94	intrusive	0.4	75	2	20	45
S78-97	intrusive	-0.2	95	4	5	60
S78-98	intrusive	0.5	115	-1	11	35
S78-120	intrusive	0.3	125	1	7	30
S78-124	intrusive	0.3	18	1	8	30
S78-116	intrusive	0.3	95	3	4	55

Sediment samples		Ag	Cu	Mo	Pb	Zn
S78-83	creek above Yellowjacket Mine	0.7	180	2	65	120
S78-84	creek below Last Chance Mine	0.3	350	1	150	230
S78-85	Dougan Creek	0.3	145	-1	55	140
S78-96	West Fork Creek	0.4	70	1	35	60

Mine waste samples		Ag	Cu	Mo	Pb	Zn
S78-35a	Skamania Mine	44.2	17,200	3	3500	8200
S78-43a	Last Chance Mine	1.0	740	-1	680	690

See Appendix I for sample locations.

Table 11. Threshold values for rock chip and stream sediment samples for the Pacific Northwest, and northern and southern parts of the Washougal Mining District.

Trace elements (ppm)	Ag	Cu	Mo	Pb	Zn
Northern Washougal District[1]					
plutonic rock	0.6	100	1	12	20
volcanic rock	-0.7	300	2	12	90
stream sediment	-0.4	90	1.5	28	110
Southern Washougal District[2]					
plutonic rock	0.6	323	4	30	81
volcanic rock	0.7	170	2	31	82
stream sediment	0.8	223	2	77	175
Pacific Northwest[3]					
rock chip	-0.1	50	-1	20	60
stream sediment	-1	50	-1	30	100

[1]Schriener, 1979, p. 109; plutonic rocks, 16 samples, volcanic rocks, 6 samples; stream sediments, 11 samples;

[2]this report; plutonic rocks, 9 samples; volcanic rocks, 5 samples; stream sediments, 3 samples;

[3]Field and others, 1974, p. 16.

Samples S78-35a and S78-43a were collected from the waste dumps of the Skamania and Last Chance Mines, respectively. Thus, these samples represent the best mineralization presently exposed in the southern part of the Washougal District. According to Moen (1977), copper and silver are the only two metals that have been produced from these mines.

Other samples that exhibit anomalous concentrations of trace elements are rock sample S78-81b (copper) and stream sediment sample S78-84 (copper, lead, and zinc). The stream sediment sample was collected from a stream which drains areas of known mineralization on the southeast margin of the Silver Star stock. The rock chip sample is an example of the vesicular porphyritic quartz diorite, tentatively associated with the mineralized breccia pipes of the Washougal District.

Economic Potential

The potential for further discoveries of significant base metal deposits in the southern part of the Washougal Mining District is considered to be low. Deposits in quartz veins that were formerly the major producers of the area cannot be considered viable exploration targets. Their small size and low metal content make them unsuitable for large-scale operations.

The breccia pipes of the southern part of the district are inferred to be associated with the quartz veins. At the surface, the breccias exhibit leached cappings with erratic formation of iron stain and botryoidal limonite. Supergene minerals indicative of base metal sulfides are not present. Chemical analyses of rock samples from two breccias have low trace element concentrations, which indicate that either the base metals have been leached away, or they were not present in significant amounts originally (Table 10). The lack of extensive boxwork textures indicative of copper sulfides such as bornite and chalcopyrite suggests that these minerals were never present (Blanchard, 1968). It is probable, therefore, that significant base metal mineralization does not take place in the breccias of the southern Washougal District.

Alteration and mineralization in the district are inferred to be possibly the shallow level expression of a porphyry deposit such as described by Burnham (1962), creasey (1966), Rose (1970), Lowell and Guilbert (1970), Sillitoe (1973), Guilbert and Lowell (1974), and Field and others (1974). Specifically, several attributes of the Silver Star stock and its associated mineralization and alteration suggest it to be the upward extension of a porphyry copper deposit, as described by Sillitoe (1973). These are:

(1) the presence of "epithermal" Cu-Pb-Zn-precious metal veins peripheral to the main intrusive body;

(2) the association of mineralization with a particular

porphyritic phase of the intrusion (vesicular porphyritic quartz diorite);

(3) the numerous hydrothermal breccia pipe systems;

(4) the spatial association and apparent co-magmatic relationship between the intrusive stock and the overlying volcanic pile; and

(5) the presence of widespread propylitic alteration, with structurally localized patches of phyllic alteration.

GEOLOGIC SUMMARY

The Washougal Mining District is located in southern Washington, on the western slopes of the Cascade Range. Bedrock of the area consists of Tertiary volcanic and volcaniclastic rocks, intruded by a sequence of epizonal plugs including the Silver Star stock.

The oldest rocks of the Washougal District have been informally termed the East Fork formation. This thick sequence (approx. 700 meters) of interstratified lava flows of basalt and andesite, laharic breccias, and tuffs is correlated with the Ohanapecosh Formation defined by Fiske, Hopson, and Waters (1963), and Wise (1970). The East Fork formation is interpreted to have been deposited in part subaerially, and in part subaqueously. Deposition occurred during late Eocene to middle Oligocene time. The East Fork formation was uplifted, folded, and subjected to erosion during the middle Oligocene Epoch. The Skamania formation, a sequence of basalt and basaltic andesite flows, was subsequently deposited upon this eroded surface. These flows were deposited under predominantly subaerial conditions, which continued from middle Oligocene to possibly early Miocene time.

The East Fork and Skamania formations were intruded by the Silver Star stock. The stock is composed of at least six intrusive phases. Each is successively more enriched in silica and K_2O, and depleted in MgO, CaO, Al_2O_3, and FeO, with the exception of one reversal for this trend. Such chemical variations are indicative of a rock suite derived from a single differentiated magma. The alkali-lime index for intrusive phases of the Silver Star stock plots at 60.8 percent SiO_2, and represents a highly calcic calc-alkaline rock series. Emplacement is inferred from crosscutting field relationships and data from other intrusions of the Washington Cascades to have occurred during middle Oligocene to possibly early Miocene time. Volcanic rocks that form the upper flows of the Skamania formation are possibly the surface expression of the intrusive activity of the Silver Star stock, as deduced from (1) their chemical concordancy with the calc-alkaline trend of the Silver Star stock; (2) their relatively unaltered condition in comparison to the basal units of the formation; and (3) their spatial position overlying the stock.

Joint patterns and a shear zone constitute the two most important structural features of the Washougal District. The joints are nearly vertical, trend northwest, and are found cutting all three major rock units of the district. Attitudes of these joints parallel the trend of the mineralized veins on the southeast margin of the stock. The second feature is a shear zone system that trends north-northeast, but is exposed in only two small areas in the southern part of the Silver Star stock. However, they have apparently localized mineralization in the northern part of the Washougal District (Heath, 1966).

The alteration mineral assemblages formed by hydrothermal alteration in the southern Washougal District are similar in part to those found in porphyry copper terrain elsewhere (Lowell and Guilbert, 1970; Rose, 1970; Guilbert and Lowell, 1974). Although minerals of the potassic and argillic alteration assemblages are not present, those of the phyllic and propylitic assemblages are common. The phyllic alteration assemblage includes quartz, sericite, and small amounts of pyrite and tourmaline. They are restricted in occurrence to within mineralized veins, shear zones, and breccia pipes. Propylitic alteration forms a widespread contact aureole within and around the perimeter of the Silver Star stock. It is characterized by the minerals epidote, chlorite, uralite, calcite, and minor albite. In addition to these hydrothermal assemblages, an albite-epidote hornfels of contact metamorphic origin is recognized locally on the southeast margin of the stock. It is characterized by the same mineral assemblage as the propylitic zone, but with additional biotite.

Metallic mineralization in the southern part of the Washougal Mining District is present as sulfides of copper, lead, and zinc, with minor amounts of iron, and silver and gold. They occur in nearly vertical, northwest-trending quartz veins on the southeast margin of the Silver Star stock and in the adjacent volcanic host rocks. The district is marked by a crude zonation of hydrothermal minerals, with sulfides of copper predominating over those of lead and zinc near the intrusive contact (Heath, 1966).

The mineralized veins are interpreted to have served as channelways for ascending hydrothermal fluids that formed the breccia pipes of the district. Where these heated fluids reached a level at which boiling occurred (P_{H_2O} greater than P_{total}), chemical and mechanical reactions between wall rock and fluid formed rock flour of the matrix and quartz-sericite alteration of the clasts in the breccias. It is inferred that these breccias, prior to erosion, graded upward into the tourmaline-rich breccias that are common to the northern part of the Washougal District.

The potential for future discoveries of economic mineral deposits in the southern part of the Washougal District is judged to be low because of: (1) the lack of significant metallic mineralization in the breccia pipes; (2) the limited extent and metal content of the quartz-sulfide veins; and (3) the lack of extensive hydrothermal alteration of the types commonly associated with mineralization in porphyry copper type terrain.

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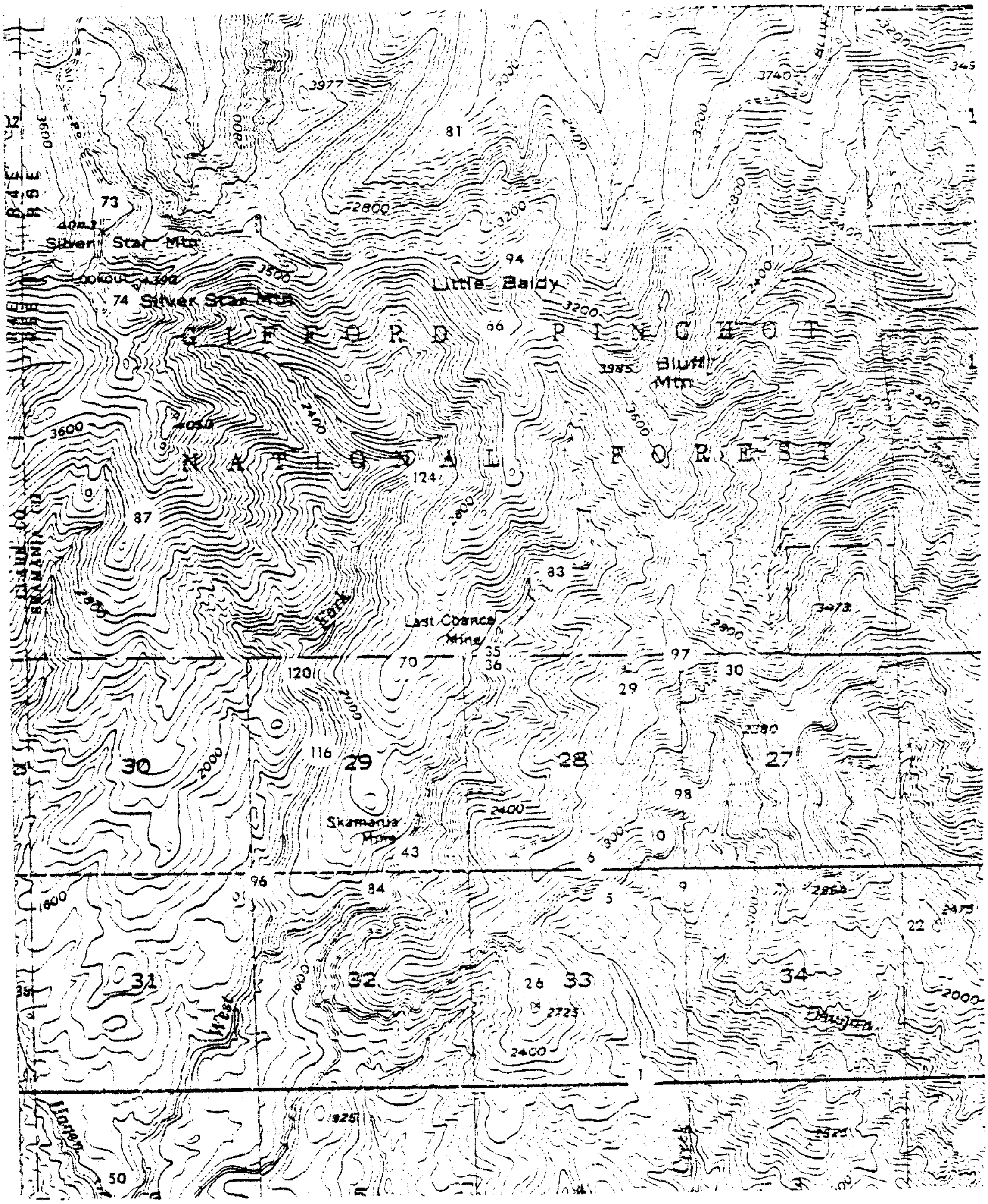
APPENDIX



APPENDIX I: Sample Locations