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GEOTHERMAL SYSTEMS IN THE CASCADE RANGE IN OREGON: INSIGHTS FROM A FOSSIL SYSTEM, NORTH SANTIAM MINING AREA, WESTERN CASCADES

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ABSTRACT

Two volcanic sequences bounded by erosional unconformities compose the stratigraphy of the North Santiam mining area, Western Cascades, Oregon. Diorite, granodiorite, and leucocratic quartz porphyry dikes, stocks, and sills, contact metamorphic aureoles, breccias, and complicated stratigraphic relations characterize a volcanic center for the older sequence in the center of the mining district. The younger volcanic sequence is associated with a volcanic center located southeast of the center of the district. Alteration destroyed porosity within the rocks of the older sequence. Circulation of geothermal fluids has been restricted to northwest-trending structures and the margins of dikes and intrusions that occupy these structures. Zones of rising hot water are characterized by silicification associated with potassic and phyllic alteration and tourmalinization. Fossil geothermal systems can serve as a model for exploration in the Cascade Range.

INTRODUCTION

The migration of heated aqueous solutions along permeable zones is fundamental in active geothermal systems and within fossil geothermal systems currently being mined for the metals they contain (eg. Bonham, 1983; Fournier, 1983). Within volcanic arc terranes, the development of hydrothermal mineral deposits and geothermal systems are closely related (Hedenquist and Henley, 1985; Ahmad and others, 1987). However, the opportunity to examine the relations between hydrothermal mineralizing processes and geothermal activity is not easily found.

The Cascade Range in Oregon is an area of active exploration for geothermal resources. The young stratovolcanoes, thick sequences of Pliocene to Recent volcanic rocks (Priest, 1982; Priest and others, 1983) and anomalously high heat flow along the axis of the range (Blackwell and others, 1978; Black and others, 1983) have encouraged this exploration activity. Although encouraging results have been obtained (Priest and others, 1987), a commercially exploitable resource has not been defined.

Since the development of a geothermal resource requires knowledge of heat transfer through the movement of an aqueous solution, an investigation of the pathways along which fluids migrate and the alteration of the volcanic rocks through which fluids pass is of value in directing explortion efforts. The Western Cascades province of Oregon contains several mineralized districts that have been deeply incised by streams that flow westward into the Willamette Valley. In the North Santiam mining area (Figure 1) mineralization and alteration patterns are exposed that allow reconstruction of the volcanic, structural, and fluid migration history within the volcanic pile.

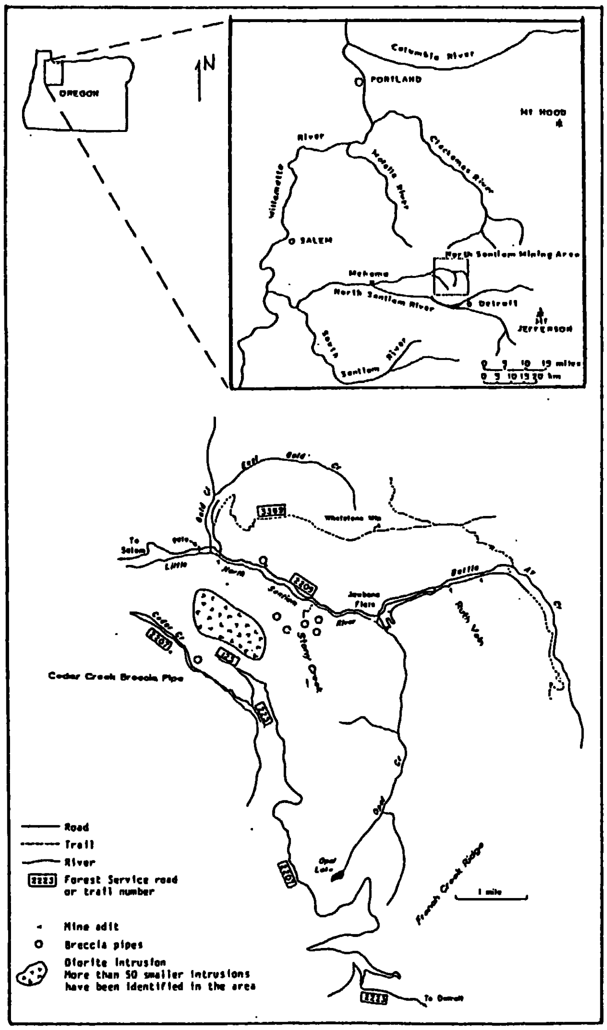

Figure 1. North Santiam mining area

We will present the stratigraphy of the area, the distribution and occurrence of alteration minerals, and the composition and temperature of the fluids responsible for mineralization and alteration. A general model for the development of mineralization and alteration, fluid-flow within the volcanic pile, and the implications of the fossil geothermal system in the district for exploration for geothermal resources in the Cascade Range will be discussed.

BACKGROUND

The North Santiam mining area was first explored for gold in the 1860's. The Ruth Vein was discovered in the early part of this century near the eastern end of the mining district and has been the focus of mining efforts for zinc and lead periodically since its discovery. Callaghan and Buddington (1938) presented a geologic and mineralization overview of the district as part of a study of the five mining districts in the Western Cascades of Oregon. A stratigraphic and alteration study of the district was prepared by Olson (1978) in which tourmaline-bearing breccia pipes along the Little North Fork of the Santiam River were described. The district was argued to represent the upper levels of a porphyry copper system (Olson, 1978; Power, 1984). A copper-mineralized breccia pipe along Cedar Creek was described by Winters (1985). This breccia pipe is within a claim block maintained by Amoco Minerals Co.

In 1982 the first of a series of studies at Portland State University was initiated to determine the relationships among stratigraphy, hydrothermal alteration, and structure in the

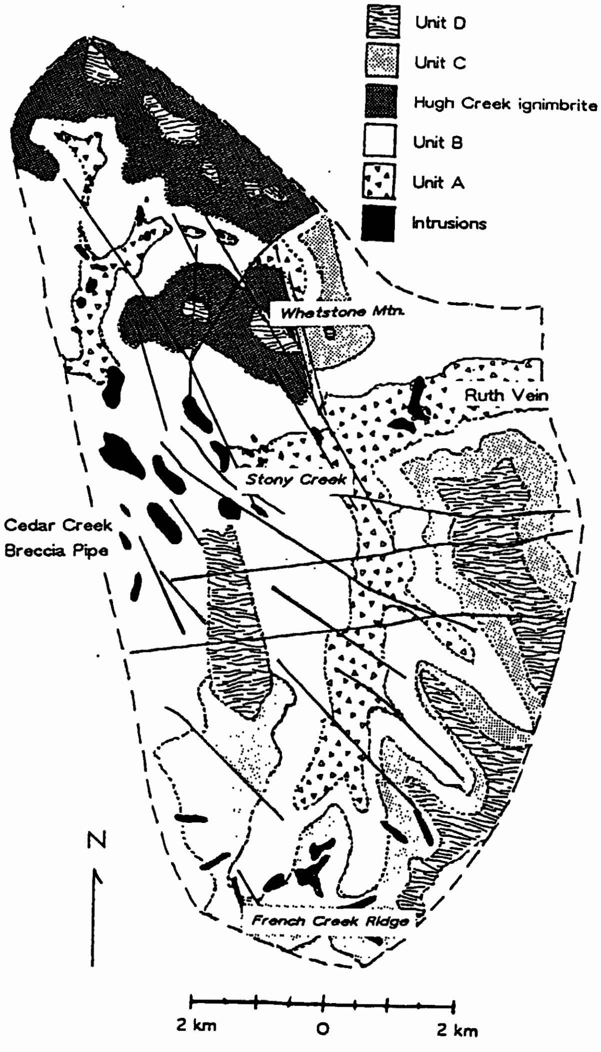

Figure 2. Geologic Map--North Santiam mining area

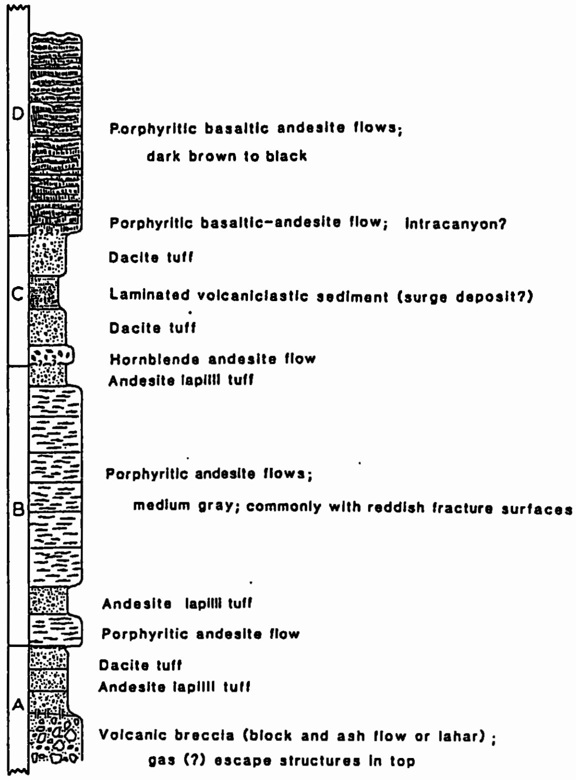

Figure 3. Composite Stratigraphic Section

district. Pollock (1985) and Pollock and Cummings (1985, 1986) presented results on the eastern portion of the district in the area of the Ruth Vein. Thompson (in progress) and Mestrovich (in progress) have continued the stratigraphic, alteration, and structural study in the central part of the district. These studies were integrated to examine the processes active in the subvolcanic portion of a porphyry copper system (Pollock and others, 1986).

STRATIGRAPHY

The volcanic stratigraphy of the study area is characterized by its complexity in both the horizontal and vertical directions. This complexity results from the nature of the original depositional environment of the volcanic rocks, the structural development which was occuring simultaneous with alteration and mineralization, and the large number of intrusive bodies which intrude the volcanic pile.

The stratigraphy has been generalized into four volcanic rock units designated A-D in Figures 2 and 3. Units A and B, and Units C and D are sequences of volcanic rocks believed to be genetically related. Units A and B are distinguished from each other by the relative abundance of fragmental rocks and flows in the section. Unit A consists of andesitic tuffs and tuff breccias. These fragmental rocks include a block and ash flow at the base of the exposed section. The block and ash flow is overlain by lapilli tuffs. Outcrop heights within the lapilli tuff sequence suggest that the thickness of individual cooling units ranges from 10 to 50 m. Flattened lapilli and pumice fragments in some tuffs suggest local welding. The fragmental deposits of Unit A are overlain by Unit B consisting primarily of lava flows of andesitic composition. Unit B is exposed at a lower elevation in the northern and western part of the district where it is spatially associated with intrusions and intrusion-related breccias.

As a sequence, Units C and D are bimodal in lithologies. Unit C is composed of andesitic to dacitic or rhyodacitic tuffs and hornblende andesite flows. The base of unit C occurs at about 1400 m on Whetstone Mountain and at about 1100 m on French Creek Ridge. Pollock (1985) described a finely laminated unit within Unit C and argued that this unit was a surge deposit erupted from a volcanic center on French Creek Ridge. Thompson (in progress) described the vent complex for these units in the vicinity of French Creek Ridge as containing crude radial dikes, abundant sills and dikes, chaotic breccia deposits, and a dacite dome (also reported by White, 1980).

Mestrovich (in progress) reports a distinct large-volume hornblende rhyodacite tuff at elevations above 900 m in the northwestern portion of the map area (Figure 2). This tuff, which is correlated with the Hugh Creek ignimbite (Dhyrman 1975; Hammond and others, 1980), is believed to have a source to the north of the area and has not been identified south of the Little North Fork of the Santiam River. This tuff is of a similar composition and apparently similar stratigraphic position to Unit C in the rest of the study area.

Unit D is composed of dark-colored porphyritic basalts and basaltic andesite flows. These flows are intracanyon into the tuffs of the Unit C. In the French Creek area (Thompson, in progress) describes similar rocks occurring as stocks and dikes.

Correlations of the rocks in the district with designated units of other researchers is tentative. All rocks of the district were assigned to the Sardine Formation by Peck and others (1964). Olson (1978), recognized that two distinct sequences were present but continued to assign both to the Sardine Formation. Southeast of the mining area, White and McBirney (1979) separated the Elk Lake formation from the older Sardine Formation on the basis of exposures in the Elk Lake area. This formation is reported to be composed of rhyodacititic to basaltic tuffs and lavas similar to Units C and D of this study. They placed the Elk Lake formation as overlying and separated from the Sardine Formation by an angular unconformity.

Dark lavas from the Elk Lake formation of White (1980) have been mapped as being continuous into the flows which cap ridges in the mining area. Within the mining area, the Sardine Formation is exposed at lower elevations in valley floors and walls; the Elk Lake formation underlies the ridge tops (Pollock, 1985; Thompson, in progress; Mestrovich, in progress). The contacts between the Sardine Formation and the Elk Lake Formation in the district suggest an unconformity with deposits of the Elk Lake deposited on a mature topography eroded into the surface of the Sardine Formation. Evidence that this unconformity is angular has not been identified in the district; however, exposures are poor and this can not be ruled out.

INTRUSIONS

Intrusions are common within the Sardine Formation but are sparse within the Elk Lake formation except in the vent area on French Creek Ridge. Within the Sardine Formation, Olson (1978) described intrusions ranging in composition from basaltic andesite to quartz latite/rhyodacite.

Pollock (1985) distinguished three intrusive types in the eastern portion of the mining area. These include an equigranular diorite, a porphyritic diorite, and a leucocratic quartz-feldspar porphyry. The equigranular diorite and porphyritic diorite form northwest-trending dikes that have vesicluated margins, sharp contacts against the country rocks, and narrow chilled margins. The leucocratic quartz-feldspar porphyry forms irregular dike and sill-like masses that range from steeply dipping to nearly horizontal.

In the central portion of the district Thompson (in progress) described the most abundant intrusions as porphyritic diorites to granodiorites. The intrusions occur as dikes and plugs that commonly have strongly brecciated margins. Xenoliths of the volcanic country rocks are common and hornfels zones are wide and well-developed (Mestrovich, in progress; Thompson, in progress). These intrusions are found only within the Sardine Formation and are spatially associated with tourmaline-bearing breccias.

The geometry of intrusions within the Sardine Formation changes from sharp-walled dikes that are strongly controlled by northwest-trending fracture and fault sets in the eastern part of the mining area to irregularly shaped stocks and plugs in the central part of the area. The irregularly shaped intrusions are aligned along northwest-trending structures or are elongate along this trend, however the overall shapes of the intrusions are not constrained by structures.

Dacite and basaltic andesite dikes occur in a radial pattern within a vent area for the Elk Lake formation on French Creek Ridge. These intrusions are not strongly influenced by the dominant structural trends in the area.

ALTERATION AND MINERALIZATION

The most prominent hydrothermal alteration is developed within rocks of the Sardine Formation. Alteration of the volcanic sequence can be divided into two main groups that are related to the water/rock ratios during hydrothermal alteration. Where water/rock ratios were low, the alteration approximates isochemical recrystallization under low-grade metamorphic conditions. Where water/rock ratios were high, the alteration results in total replacement of the primary lithology. Mineralized veins, manifestations of ancient geothermal activity, occur within these zones of strong replacement.

The most intense alteration within the Sardine Formation is distributed relative to prominent northwest-trending structural zones. The volcanic and intrusive rocks between these structural zones may be weakly altered and the indicated alteration approximates isochemical alteration.

Primary minerals and textures are well-preserved within rocks altered under low water/rock ratios. Weakly altered intrusions and volcanic rocks display partially to completely pseudomorphed primary igneous minerals. Carbonate, epidote, and albite commonly replace plagioclase; chlorite, calcite, epidote, and uralite replace primary mafic minerals. The primary porosity in rocks altered under these conditions has been destroyed. This alteration is best classified as propylitic alteration.

Within rocks altered under moderate to high water/rock ratios, primary igneous textures are strongly modified or destroyed and significant changes in bulk composition of the rocks are noted. These zones are also characterized by development of K-silicates and silicification.

Five types of alteration attributed to moderate to high-water rock ratios are present in the district. These include 1) potassic, 2) phyllic, 3) tourmalinization, 4) silicification and 5) argillic. Silicification commonly accompanies phyllic alteration and tourmalinization.

Potassic alteration is characterized by conversion of minerals to secondary sericite, K-feldspar, biotite associated with silicification. It is restricted to areas around tourmaline-bearing breccia pipes and is not present above an elevation of about 850 m. The potassic alteration overprints textures and minerals formed by earlier propyllitic alteration.

Phyllic alteration is characterized by development of sericite, illite, kaolinite, quartz, and pyrite, and destruction of primary rock textures. This alteration is best-developed along northwest-trending faults, around tourmaline-bearing breccia pipes, and along intrusive margins. Phyllic alteration is commonly developed around mineralized quartz veins as is the case at the Ruth Mine (Pollock, 1985). This alteration occurs throughout the central and eastern portion of the district.

Tourmalinization occurs in breccia pipes and the adjacent country rocks. The tourmaline-bearing breccias are elongate along north-west-trending structures, and are 120-200 m long and 25-70 m wide. No tourmaline-bearing alteration was found above 730 m. The breccias are developed in granodiorite and porphyritic diorite intrusions and adjacent tuffs and flows of the Sardine Formation.

Silicification is the dominant alteration within the margins of tourmaline-bearing breccias and extends into wall rocks. Chlorite, sericite, and microveinlets and starbursts of tourmaline occur within the silicified margin. Pyrite is locally abundant. Breccia fragments within the structures are commonly porphyritic. Mafic phenocrysts are replaced by epidote, chlorite, magnetite, and sphene; plagioclase phenocrysts by sericite, albite, clay, and quartz; the groundmass by quartz, albite, sericite, chlorite, and clay. Tourmaline occurs as radiating clusters with quartz within clasts, and veinlets cutting the silicified matrix of the breccia. Chlorite and tourmaline commonly rim clast boundaries and extend into the matrix of the breccia.

Argillic alteration is characterized by replacement of primary minerals as well as alteration minerals by kaolinite. It is best developed along fault zone breccias and intrusive margins. The argillic alteration occurs along the crest of Stony Creek Ridge (Thompson, in progress) and in the eastern end of the district, such as at the Ruth vein (Pollock, 1985).

Alteration within the Elk Lake Formation is not prominent. Alteration of the volcanic rocks is slight or, where present, occurs as cementation of the fragmental volcanics. Precipitated minerals occur along fractures and within vesicles of the volcanic rocks. Pollock (1985) reported calcite + chlorite veins and cement in tuffs of the lower Elk Lake Formation (Unit C) on Whetstone Mountain. Precipitated zeolites and calcite occur commonly. Laumontite and stilbite are commonly found along French Creek Ridge (Thompson, in progress).

Winters (1985) described the alteration in the area of the copper-mineralized Cedar Creek breccia pipe. Two overlapping stages of hydrothermal mineralization occur, both dominated by a phyllic alteration assemblage. Tourmaline rossettes and minor disseminated chalcopyrite accompany the replacement of breccia fragments by fine grained quartz, sericite, chlorite, and carbonates in the first stage. In the second stage, open space quartz, sericite, chlorite, tourmaline, apatite, hematite, chalcopyrite, bornite, molybdenite, tetrahedrite, pyrite, galena, and sphalerite were deposited. The sulfides formed late in this stage. A final stage of minor carbonate veining accompanied by siderite and kaolinite was also recognized.

Multiple stages of brecciation are noted throughout the district. Within the tourmaline-bearing breccias, these mutiple stages are represented by clasts of previously tourmalinized material within a tourmaline matrix (Thompson, in progress; Mestrovich, in progress). Additional styles of brecciation within the pipes range from granulated matrix-dominated breccias to shatter breccias depending on position relative to the focii of brecciation or as a result of multiple stages of brecciation (Mestrovich, in progress).

Faults, predominately with a northwest trend, are present throughout the district and serve as the primary locations of alteration and mineralization in areas away from intrusions. Movement on these faults is very difficult to determine due to the lack of recognizable marker horizons and features in the volcanic rocks and intrusions. Slickensides, where present, are generally nearly horizontal.

FLUID COMPOSITION AND TEMPERATURE

Microthermometric analysis of fluid inclusions have been performed on samples in various settings of the district (Winters, 1985; Pollock and Cummings, 1986; Thompson, in progress).

In the eastern portion of the district filling temperatures range from 218 to 287° C. These samples were quartz grains from quartz-calcite veins within zones of silicificiation near the eastern edge of the district. The data in this area are sparse, but suggest the temperatures in the veins increases to the west. Salinities are low and freezing point depression ranges from -.6 to -3.8° C (Pollock and Cummings, 1985).

Thompson (in progress) examined fluid inclusions within quartz-tourmaline, quartz-sericite-tourmaline, pyrite-quartz veins, and in phyllic alteration in the Stony Creek Ridge area. The homogenization temperatures suggest three groupings; 190-220° C, 270-305° C, and 310-340° C. Salinities are less than 10% NaCl equivalent, the majority between 3 and 5% NaCl equivalent. The inclusions are two-phase NaCl-H_2O inclusions. CO_2-bearing inclusions occur as secondary inclusions within quartz phenocrysts from propylitically altered granodiorite, and calcite-quartz veins in the Stony Creek area. Homogenization temperatures range from 270 to 300° C, and composition is 8 to 17% NaCl equivalent.

Winters (1985) examined the fluid inclusions in the copper-mineralized Cedar Creek Breccia pipe. Overall, inclusions from the Cedar Creek breccia pipe are significantly higher in temperature of homogenization and contain higher salinities than those from the Stony Creek breccias or the eastern portion of the district. Four types of fluid inclusions were recognized that range from low to moderate salinity vapor and liquid inclusions to high salinity, high temperature inclusions containing halite, sylvite, and up to two additional daughter minerals. CO_2-bearing inclusions were not reported by Winters (1985).

DISCUSSION

The stratigraphic evolution of the North Santiam mining area has been determined in order to place the hydrothermal alteration and mineralization within the context of the developing volcanic pile. The available data indicate two volcanic cycles, each associated with a hydrothermal system of differing characteristics. The older of the two systems is associated with volcanic rocks and intrusions of the Sardine Formation. The alteration and mineralization styles resemble those expected in the subvolcanic portion of a porphyry copper system (Olson, 1978; Power, 1985; Pollock, 1985; Pollock and Cummings, 1985; Pollock and others, 1986; Thompson, in progress; Mestrovich, in progress). The younger hydrothermal system developed in response to a volcanic center on French Creek Ridge. This system displays characteristics consistent with a relatively shallow geothermal system.

Radiometric age determinations for the volcanic rocks of the North Santiam mining area are sparse and have been determined by K-Ar systematics. The age of a porphyritic diorite intrusion in the Sardine Formation was reported as 13.4 ± 0.9 m.y.B.P. (Power and others, 1981a). The age was determined on a hornblende separate from the intrusion. Fluid inclusion data on veins from this area indicate that fluid temperatures potentially as high as 300° C accompanied alteration and may have influenced this date. It is our opinion that this date is a minimum date for the development of the volcanic center for the Sardine Formation exposed in the central portion of the district.

Rocks of the Elk Lake formation have been dated by White (1980) and, in the area of French Creek Ridge, age determinations range from 11.8 to 11.0 m.y.B.P. Two dates (12.0 ± 0.4 and 12.5 ± 0.4 m.y.B.P.; Hammond and others, 1980) have been reported for the Hugh Creek ignimbrite.

Power and others (1981b) report a date of 11.0 ± 0.4 m.y. B.P. for sericitic alteration in a quartz diorite collected in the area of the Stony Creek tourmaline-bearing breccias. This age was argued to represent the time of porphyry mineralization in the district.

The stratigraphic relations in the district indicate that two volcanic centers of different age are exposed. The central portion of the district apparently was a volcanic center during the eruption of the Sardine Formation. This is suggested by the volcanic lithologies, complex stratigraphic relations, widespread contact metamorphic aureoles, and the wide variety of intrusive and fluidization breccias present in this area (Mestrovich, in progress). The time of development of this center is unclear because of the uncertainty in the interpretation of available radiometric age dates. The age appears to be older than 14 m.y. B.P. The second center was active during the eruption of at least part of the Elk Lake formation from French Creek Ridge. The age of this center is approximately 11.8 to 11.0 m.y. B.P. The Hugh Creek Ignimbrite that crops out in the northwestern part of the study area was deposited approximately 12.2 m.y.B.P. from a volcanic center outside of the study area.

The contact relations between the rocks of the Sardine Formation and the Elk Lake formation is an errosional unconformity at the top of the Sardine Formation. This unconformity is a topographically mature surface that was developed to a stratigraphic level within the Sardine Formation so as to expose the intrusions within the volcanic center. The depth of erosion was into the zone of propylitic alteration represented by the epidote + chlorite + calcite + albite assemblage in the rocks altered under low water/rock ratios. The erosion surface was buried by the eruption of the Elk Lake formation as the French Creek center began to develop.

Relating the timing of alteration to the time of development of the volcanic centers is less straight forward than the age of the volcanic centers. The alteration patterns within the Sardine Formation indicate overprinting of earlier widespread propylitic alteration by phyllic and potassic alteration along structures, dike margins, and tourmaline-bearing breccias on Stony Creek. Fluid inclusions indicate that the phyllic alteration occured under temperatures less than 350° C. The lack of boiling indicators suggests depths of burial at the time of alteration as being at least 1200 m. Paragenetic relations indicate that early solutions within these breccia pipes were CO_2-bearing and that later solutions were dilute water-rich solutions.

The distribution of phyllic alteration indicates close control by fractures and faults. The Stony Creek breccia structures are distinctly aligned along northwest-trending structures. The location of these breccias and the general distribution of phyllic alteration and vein mineralization suggests that permeable zones occurred along open structures or along the margins and within intrusions that display cooling joints.

The Cedar Creek breccia pipe (Winters, 1985) contains fluid inclusions that indicate solution chemistry and temperatures substantially different from those encountered in the Stony Creek breccia structures and in the eastern part of the district. The Type-I inclusions would indicate depth of burial needed to prevent boiling to be greater than can be generated from the preserved volcanic pile in the area. This observation is in reasonable agreement with the depth of erosion inferred from field relations at the top of the Sardine Formation.

The field relations, fluid inclusion data, mineral assemblages, and alteration textural relations, indicate that the Cedar Creek breccia pipe may have developed within the volcanic center that deposited the Sardine Formation in the area. The Stony Creek breccias and base metal veins present in the eastern portion of the district were deposited from a geothermal system that operated in the area at the time of the French Creek volcanic center from which at least part of the Elk Lake formation was deposited. However, the distribution of dikes within the Sardine Formation indicate that the same northwest-trending structures were as influential in controlling fluid movement in the volcanic pile during the life of the younger geothermal system as they were during emplacement of dikes and intrusions associated with the Sardine Formation.

The alteration mineral assemblages found along the northwest-trending structures are associated with silicification of the country rocks and deposition of tourmaline and/or base metals with quartz. Phase relations indicate that quartz is deposited from ascending and cooling solutions (Fournier and Rowe, 1966; Giggenbach, 1981). These relations indicate that the major zones of fluid up-flow in the North Santiam mining area were along the northwest-trending structures and was confined largely to the faults, the margins of dikes that occupy the faults, or within zones where porosity was generated during alteration as occurred during development of the Stony Creek tourmaline-bearing breccia structures. The silicification is associated primarily with mineral assemblages including quartz-tourmaline- chalcopyrite and quartz-sericite-pyrite.

CONCLUSIONS

The stratigraphy, structure, and hydrothermal alteration in the North Santiam mining area indicate the following patterns related to fluid flow within the Cascade volcanic province:

1. The volcanic pile is composed of potentially thick, unconformity bounded stratigraphic sequences that were erupted at different times. These sequences may be separated by significant erosional unconformities across which volcanic products and potentially alteration mineral assemblages may change. Within the unconformity bounded sequences the stratigraphic relations may vary considerably both laterally and vertically.

2. The porosity of older volcanic packages may have been destroyed by earlier hydrothermal alteration and may be largely impermeable to solutions migrating in younger geothermal systems. After the primary porosity is destroyed, the only zones of permeability are those developed along structures and along fractured margins of dikes and intrusions. These fluid pathways may be enlarged by fracturing due to early stage degassing of CO_2-rich solutions.

3. The fluid flow pathways are along regionally common structural elements that have been present and active for a considerable length of time. The dikes and plutons that are present in the volcanic center in the Sardine Formation are controlled by the same northwest-trending structures that served as routes of fluid migration during the younger geothermal system. These structures exerted a distinct influence on the construction of the volcanic pile and the migration of fluids within it. The length of time these structures were influential is measured in terms of millions of years if not tens-of-millions of years.

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