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Results of Test Drilling at Newberry Volcano, Oregon

—and some implications for geothermal prospects in the Cascades

by
Edward A. Sammel
U.S. Geological Survey
Menlo Park, California

Abstract

Test drilling by the Geothermal Research Program of the U.S. Geological Survey (USGS) in the Newberry caldera, a large Quaternary volcano located immediately east of the Cascade Range in west-central Oregon, has demonstrated that high-temperature (265°C) geothermal fluid exists in permeable rocks at a depth of 930 meters. Heat flow beneath the caldera floor may be about 1500 milliwatts per square meter, but much of the heat is dissipated by ground-water flow at shallow depths, thereby effectively masking the geothermal anomaly.

During a flow test in the drill hole, initial well-head pressure was 57 bars, and the initial mass flow rate was approximately 1.5 kilograms per second. Most of the fluid discharged consisted of steam and carbon dioxide. The liquid discharged appeared to be predominantly condensed steam.

Geophysical studies in the Cascade Range have previously encouraged the belief that the geothermal potential in the area is high. The results at Newberry appear to confirm this belief and provide incentives for additional exploration over a large area of Washington, Oregon, and California.

Introduction

Newberry Volcano in west central Oregon has been a source of interest to geothermal investigators during at least the past decade. The young rhyolitic deposits and active fumaroles in the caldera of this large volcano, as well as the hundreds of cinder cones, fissure vents, and pumice rings on the flanks of the mountain have intrigued geologists for many years and have been the focus of numerous recent investigations. Studies by Peterson and Groh (1969); MacLeod, Walker, and McKee (1975); and MacLeod and others (1981), in particular, suggest the possible significance of the area as a source of geothermal energy. Estimates by Brook and others (1978), based largely on the presence of fumaroles and analogies to other Quaternary volcanoes, have indicated that temperatures in a geothermal reservoir at Newberry might be as high as 250°C. During the past summer (1981), test drilling by the U.S. Geological Survey (USGS) demonstrated the presence of even hotter geothermal fluids at moderate depths beneath the caldera floor.

Newberry Volcano, centered about 40 kilometers (km) south of Bend, Oregon (Figure 1), is among the largest Quaternary volcanoes in the conterminous United States. Its caldera has an area of nearly 45 square kilometers (km^2) and the volcano and its lava flows cover an area greater than 1200 km^2. Paulina Peak, the highest remnant of the former mountain, stands at an altitude of 2434 m on the rim of the present caldera. The altitude of the caldera floor is 1932 m, which is about 610 m higher than the adjacent La Pine and Fort Rock valleys. Two lakes, Paulina and East, occupy much of the caldera floor and contribute to the scenic beauty of the area. The caldera is a reserved recreational area within the Deschutes National Forest and is part of the Newberry Caldera KGRA.

The flow rocks and explosive ejecta that form the volcano range in composition from basaltic to rhyolitic and were extruded over a long period in Pleistocene and Holocene time. In most respects, Newberry is similar to the Medicine Lake volcano in northern California. Like Medicine Lake, it lies a significant distance east of the main Cascade Range.

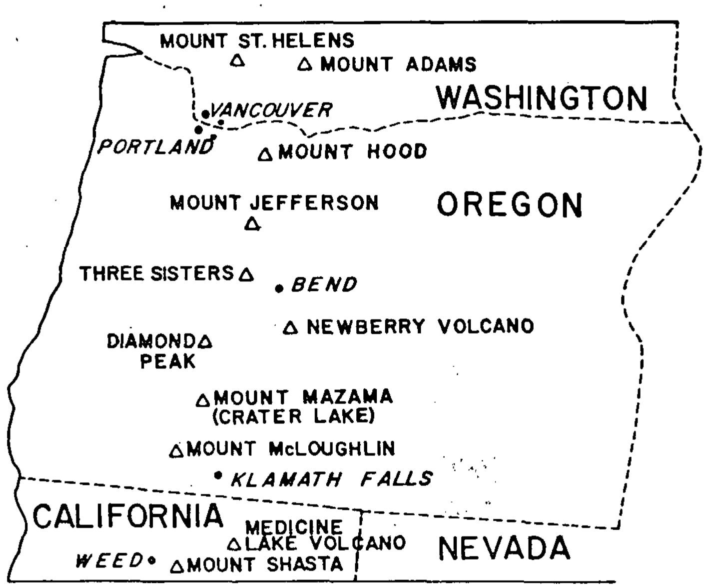


Figure 1. Map showing locations of some major volcanoes in the High Casades Range of Washington, Oregon, and California.

Although Newberry is usually grouped with volcanoes of the Cascade Range, it is not clear how its origin and history are related to the subduction zone and crustal plate collisions that have apparently been causal factors in the construction of the High Cascades. Newberry's position as the western outpost of a trend of progressively younger silicic volcanism that can be traced through central Oregon (MacLeod, Walker, and McKee, 1975) may complicate the picture but it is probably safe to assume, for the present, that volcanism at Newberry is related to the same tectonic forces that produced the Cascade volcanoes.

The most recent volcanism at Newberry occurred about 1400 years ago when rhyolitic pumice was erupted and a large mass of obsidian flowed from a vent in the caldera. Current activity is limited to a few thermal springs (probably drowned fumaroles) which occur on the margins of Paulina and East Lakes and in a small pond, "Lost Lake," adjacent to the large obsidian flow. Temperatures of these springs are generally low, but may range to at least 62°C depending on the lake levels and lake-water temperatures. Despite the fact that 1400 years have elapsed since the last eruption, "considering the long time over which eruptions took place on Newberry, the volcano should be considered dormant but capable of future eruptions. . . . " (MacLeod and others, 1981, p. 91).

Test Drilling

In 1977 the Geothermal Research Program of the USGS drilled a small-diameter wireline core hole (Newberry 1) on the flank of the volcano about 4 km northeast of East Lake at an altitude of about 1900 m. In the core hole, pumice from the eruption of Mount Mazama (about 6700 years old) was encountered at a depth of 1 m, and the drill then penetrated cinders, breccia, tuffaceous sediments, pumice, ash-flow tuffs, ash-fall deposits, and basaltic to andesitic flow rocks to a total depth of 386 m. The lava flows range in thickness from 0.3 m to 70 m and comprise only about 44 percent of the section.

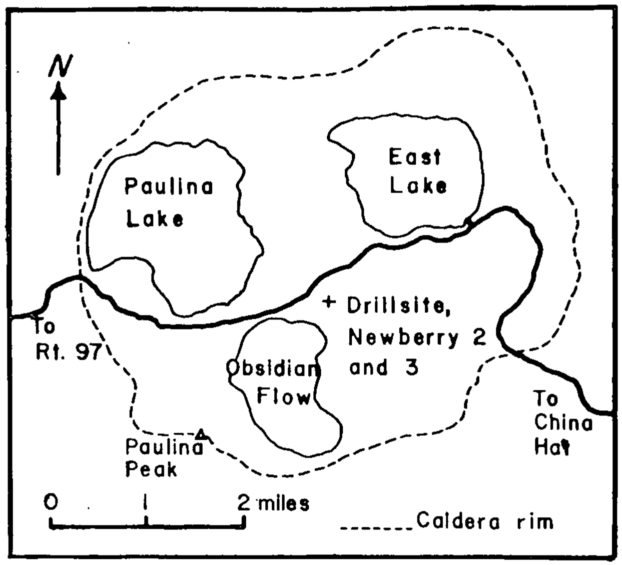


Figure 2. Map of Newberry caldera, showing the site of test holes Newberry 2 and 3.

Only small amounts of formation fluid were encountered by the drill hole, and mud circulation could not be maintained during most of the drilling. Caving was a common occurrence; as a result, the drill pipe was ultimately stuck in the hole and most of it abandoned. The hole was completed by setting 1½-inch pipe to 210 m, the final available depth, for the purpose of obtaining heat-flow measurements. The temperature profile (Figure 3) shows several zones in which ground-water flow probably affects the temperatures, notably at 154 m where the top of a black vesicular basalt flow was encountered. The maximum temperature of 9°C occurred in this zone. Because of the obvious convective disturbance, no heat-flow values have been calculated for this site.

A second test hole (Newberry 2) was spudded by the USGS in 1978, this time on the floor of the caldera, 400 m east of the big obsidian flow, at an altitude of 1935 m (Figure 2). The siting of the hole was based primarily on environmental and access criteria, although it was considered important to drill in the east half of the caldera where the more recent silicic volcanism had occurred. Rocks in the first 310 m, drilled by the mud-rotary

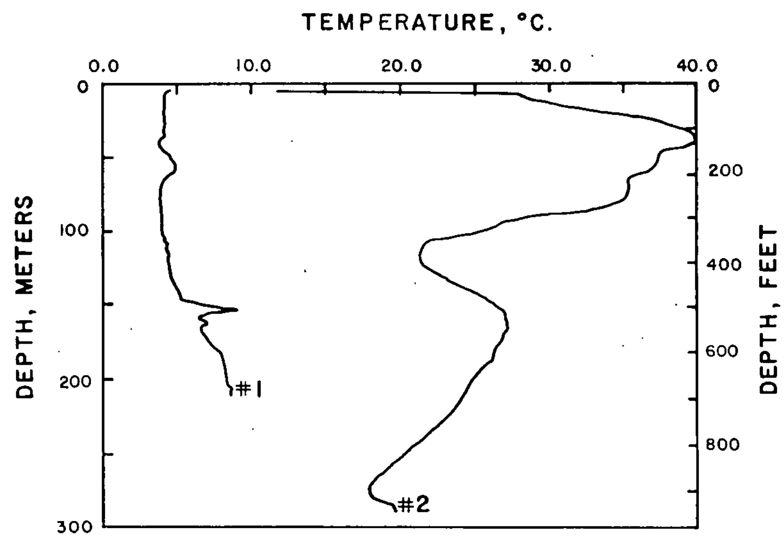


Figure 3. Temperature profiles in test holes Newberry 1 and Newberry 2. The profiles were obtained in November, 1978, one year after completion of Newberry 1 and one month after drilling to 313 m in Newberry 2.

method in order to allow for future reduction in diameter, consisted largely of pumice, cinders, ash, volcanic sediments, and thin flow rocks, similar to those in the flank hole. A notable addition was a 56-m-thick obsidian flow encountered at 42 m. The interval from 102 m to 335 m was subsequently cored in an offset hole, Newberry 3, with core recovery ranging between 40 percent in the interval 102 m to 186 m, and 87 percent from 186 m to 335 m.

Test-hole 2 was deepened by wireline coring during the summers of 1979 and 1981 as funds became available, and reached its final depth of 932 m on September 18, 1981. A highly generalized lithologic log of the hole, based on field observations of the core (Figure 5), reveals that a possibly deep lake once existed beneath the drill site (core interval 322 to 381 m), that the volcanic sediments and pyroclastic deposits which predominate in the upper 610 m give way to increasingly thick flow rocks in the lowest 320 m, and that there is an overall upward increase in the silica content of the rocks.

Permeabilities in the massive flow rocks are probably low, but breccia zones, volcanic sediments, and fractured, vesicular interflow zones may have much higher permeabilities. Loss of drilling fluids (up to 90 or 95 percent) occurred during most of the drilling in the upper 610 m of the hole, but little or no formation water entered the hole in this section. Hydrostatic pressures in the drill hole would always have exceeded possible pressures in the formations drilled, however, and the lack of formation-fluid returns does not indicate the absence of ground water in the rocks. Below 610 m, there was no increased loss of drilling fluid, and the overall permeability of the massive flow rocks in the lowest one-third of the hole is probably extremely low.

Thermal Gradients and Heat Flow

A temperature profile obtained in the upper 313 m of Newberry 2 in November 1978 (Figure 3) differs only in minor details from one obtained two and one-half years later in the same depth interval (Figure 4). During the

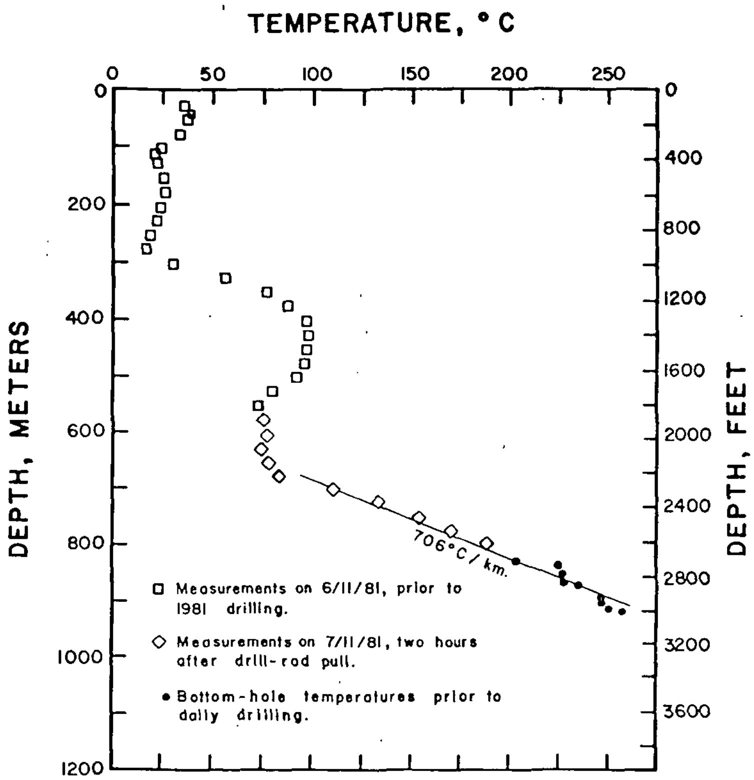


Figure 4. Composite temperature profile of Newberry 2.

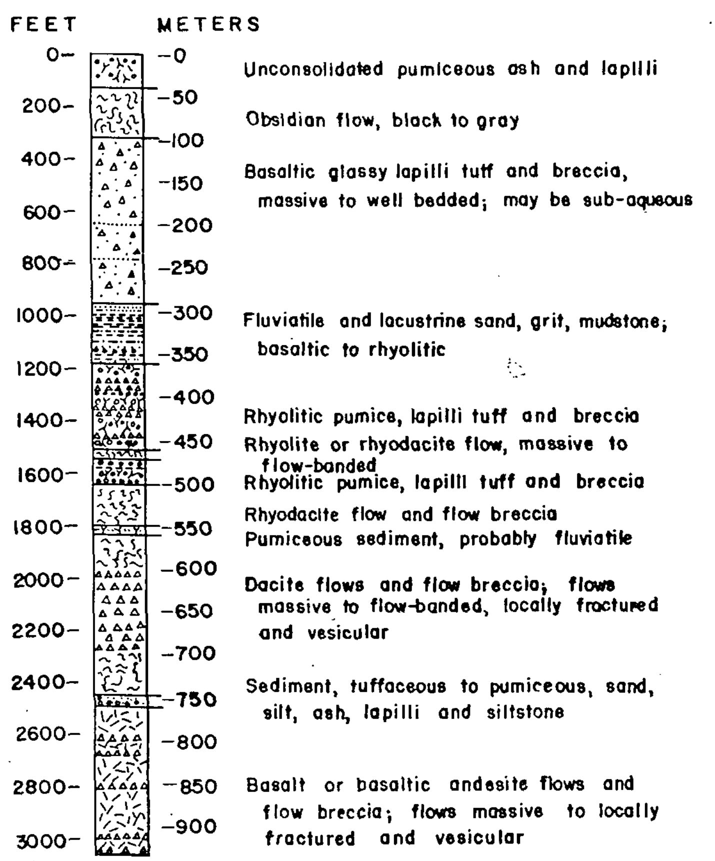


Figure 5. Preliminary generalized lithologic log of Newberry 2. Descriptions of the upper 305 m of core were made from core in the adjacent hole, Newberry 3. rock names are based solely on visual examinations and have not been confirmed by chemical analyses.

intervening time the hole had been deepened to 631 m. The warm bulges in the upper 640 m of the profile remained at virtually constant temperatures throughout the drilling period.

Most of the rocks in the vicinity of the temperature anomalies appear to have high permeabilities and probably low thermal conductivities, and the temperature profiles are probably not conductive phenomena. The probable cause of the anomalous temperatures is warm water that rises in faults or fracture zones and moves laterally in permeable zones within the crater-fill material and flow rocks. The maximum temperature in the hottest of these convective zones, near the 425 m depth, was 100°C. Between the thermal bulges are zones, as at 120, 275, 550, and 625 m, where cooler water may carry off some of the geothermal heat and redistribute it within the caldera. Nearly all these convective anomalies in the temperature profile can be correlated with core samples that appear to have higher than normal, although still low, permeabilities. The converse is not true, however, and many zones of apparently permeable rock do not show significant temperature anomalies.

Estimates of heat flow in crustal rocks are calculated from two measurable quantities, the conductive thermal gradient and the thermal conductivity of the rock. The temperature profile in the depth interval 675 to 930 m for Newberry 2 (Figure 4) provides a reasonably firm basis for an estimate of the thermal gradient. Although at least three slightly differing segments of the profile can be defined when the data are examined in detail, for the present purpose an average gradient through the entire interval is probably justified. The gradient calculated for this interval is 706°C per kilometer.

The second parameter, thermal conductivity, can be estimated, pending the results of laboratory tests on the core. A value of 5 mcal $cm^{-1}s^{-1}{}^{\circ}K^{-1}$ may be a reasonable estimate of the average conductivity of the zone, comprising as it does about 65 percent massive, unaltered basaltic andesite and andesitic flow rocks, the remainder being largely hydrothermally altered flow rocks. Using the calculated average thermal gradient and the estimated thermal conductivity, conductive heat flow through the lower part of the caldera rocks penetrated at the drill site is calculated to be about 35 Heat Flow Units (μcal $cm^{-2}s^{-1}$) or about 1500 milliwatts per square meter (mW m^{-2}). This preliminary estimate will be revised when conductivity measurements on the core have been made and evaluated. The significance of the estimate is uncertain because the origin and configuration of the temperature profile below the bottom of the drill hole are not known and because it can only be assumed at this time that the upper end of the conductive gradient is established by the convective effects of groundwater flow.

Preliminary Flow-Test Results

On September 29 and 30, 1981, a 20-hour flow test was made in Newberry 2. The producing zone was a 2-m section of altered, vesicular basaltic andesite penetrated at a depth of 930 m. Heavy mud (up to 10.8 lbs/gal) had been pumped into this zone in order to control gas emissions and high well-head pressures that were encountered at this depth 10 days previously. The drill pipe was stuck near the bottom of the 7.70-cm (3.032-inch) hole.

Flow was induced by swabbing drilling mud from inside the 6.07-cm (2.39-inch) NX wireline drill pipe to a depth of 427 m. The fluid pressure in the formation was not measured, but can be estimated from the weight of the fluid column in the drill hole as flow began. The estimated formation pressure is 62 bars (890 pounds per square inch), which is significantly higher than the pressure of saturated steam at the measured bottom-hole temperature of 265°C (52 bars-730 psi). The excess pressure is believed to be due to the partial pressures of gases in the formation. At the well head, initial pressure ahead of a 1-inch choke was 57 bars (800 psi).

Flow was allowed to continue for 20 hours while samples of fluid and gas were collected at a separator. Preliminary estimates of flow rates indicate that the initial mass flow rate from the reservoir was approximately 1.5 kilograms per second (kg/s; 12,000 lbs/hr). At the end of 20 hours, pressure at the well head had declined to 9 bars (120 psi) and the mass flow rate was approximately 0.7 kg/s (5400 lbs/hr).

Preliminary estimates of the constituents of the gas phase suggest that steam was predominant and that the noncondensable gas consisted largely of CO_2 with minor amounts of H_2S and methane. Concentrations of chloride in the liquid phase were extremely low, suggesting that the liquid was almost entirely composed of condensed steam. Chemical and isotopic analyses of the liquid and gas, to be completed during the next few months, will elucidate the composition of the formation fluids, enable more precise mass flow calculations to be made, and perhaps afford clues concerning characteristics of the geothermal reservoir.

Conclusions

It is premature to offer extensive interpretations of the drilling results or to speculate on many of their implications. The following comments can probably be made with some assurance, however.

In the setting of a recently active caldera, the high conductive thermal gradient, averaging 706°C/km through a depth interval of one-fourth kilometer, and the high temperature, 265°C at 930 meters, strongly imply the presence of a shallow crustal heat source. The distribution of post-Mazama (<6700-year-old) rhyolitic deposits over much of the eastern two-thirds of the caldera (MacLeod and others, 1981) suggests that the heat source could be a cooling, but possibly still molten, magma body. The probable smallest depth to such a body is less than 2 kilometers on the basis of an extrapolated thermal gradient and the assumption that thermal conductivity in rocks beneath the caldera does not increase with depth. The actual depth could be significantly greater than 2 kilometers and is probably indeterminate on the basis of available evidence.

Data from geophysical investigations at Newberry are in part conflicting and are at best inconclusive. Stanley (1981) found no evidence for a large magma chamber beneath Newberry in his magneto-telluric (MT) data. M. Iyer (oral commun., 1981) similarly finds no evidence in teleseismic studies made several years ago for a body of molten rock. The limit of resolution for the teleseismic data is perhaps 3 km, however. Iyer's data do show a large velocity contrast in the area, with higher velocities localized beneath the caldera. Williams and Finn (1981), on the basis of a reinterpretation of gravity data from Newberry, find a gravity high that suggests the presence of a large intrusive body, perhaps 3 km thick, at a shallow depth and extending well beyond the margins of the caldera. The teleseismic data may tend to confirm the gravity interpretation, and the MT data do not rule out the presence of a largely solidified intrusive body. Any further conclusions at this time regarding the nature and size of the heat source would be highly speculative.

The production of fluids from a zone less than 2 m thick at Newberry encourages the belief that a deeper hole might encounter additional permeable rocks that would afford larger sustained flows and perhaps even higher temperatures. The nature and origin of the geothermal fluid remain matters for speculation, however. Possible origins are: (1) the fluid encountered by the drill hole is hot reservoir water that flashed in the formation near the borehole; (2) the fluid is saturated steam at or near a boiling liquid surface; (3) the fluid is dry steam, residual from a previously saturated hot rock and/or derived from small quantities of recharge; (4) if the fluid encountered is hot water, it could be discharged upward from a deeper and presumably hotter reservoir. Although some of these possibilities seem more likely than others, a choice of the most likely must be deferred until all analyses have been completed.

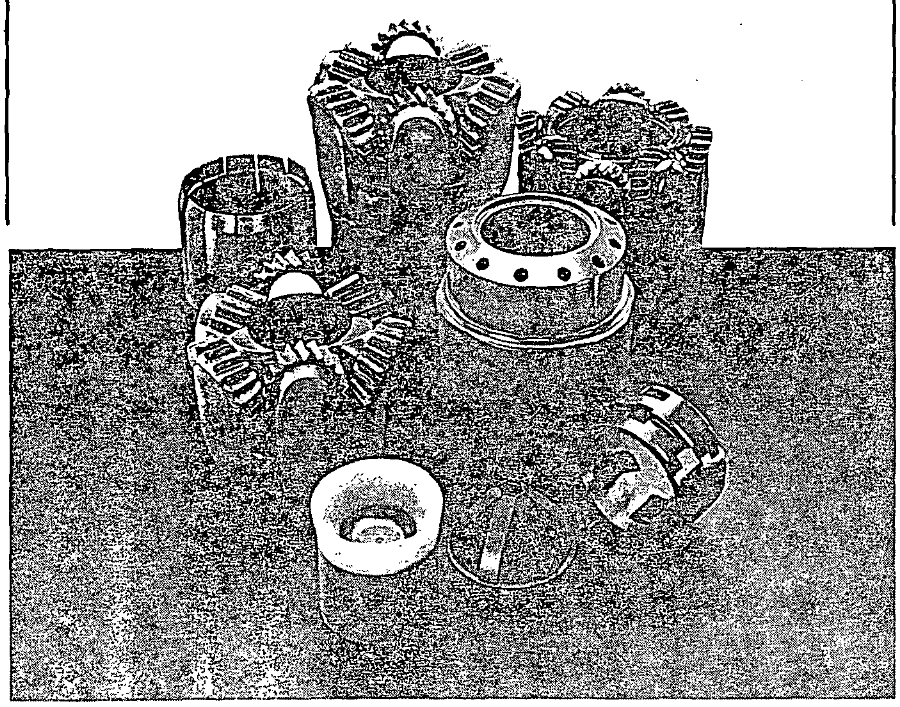
Several facts having implications for geothermal prospects in the Cascade region may be noted.

First, the underlying high-temperature anomaly and the associated conductive thermal gradient at Newberry are masked by the flow of cooler water only a short distance above. Such masking is probably common in the Cascades.

Second, preliminary analysis of the core and the temperature data from Newberry 2 suggest that small flows of ground water in permeable sections of volcanic rocks are capable of intercepting large heat flows and redistributing the heat over larger areas. The resulting convective transport of heat is likely to be predominantly lateral. An uncompleted hydrologic study by the author and colleagues suggests that at Newberry little of the precipitation percolates deep beneath the crater. The same lack of connected vertical permeability that results in sealing out the meteoric water also prevents the surface discharge of most geothermal fluids.

Third, at Newberry a mass of hot and perhaps partly molten rock either underlies the caldera at shallow depths or heats geothermal fluids at greater depths in the crust. These findings support the hypothesis of Smith and Shaw (1975) that areas of young silicic volcanism are the best targets for exploration for igneous-related geothermal systems. It is in such areas that shallow crustal magma reservoirs or cooling plutons are most likely to exist. Geologic and geophysical investigations suggest that other hidden geothermal systems may be present in the Cascade Range.

The results of the Newberry drilling, even though incomplete and, at present, ambiguous, should encourage those engaged in geothermal exploration in the Cascades and perhaps stimulate additional efforts. Whether or not new exploration occurs at Newberry Volcano, the most important outcome of the present study may be to point the way to undiscovered resources in the entire Cascade region.



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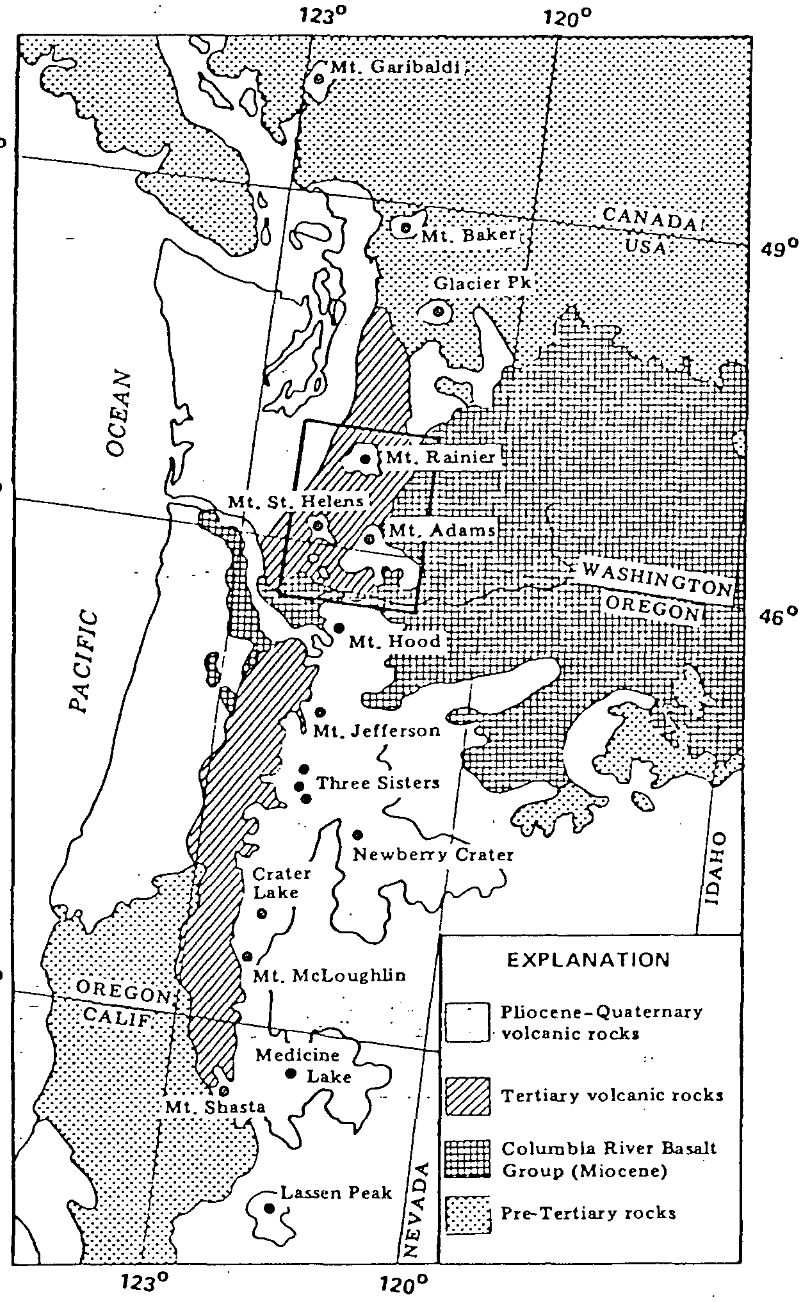

Figure 1. — Index map showing location of the Southern Cascade Mountains study area and major geologic elements of the Cascade Mountain Range (after McBirney, 1968). Dots indicate location of Quaternary Cascade stratovolcanoes.

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The Cascade Province

A. R. McBirney and C. M. White

Center of Volcanology,
University of Oregon, Eugene, Oregon 97403, USA

ABSTRACT

The Cascade Range of north-western North America is a classic example of an orogenic volcanic system of the continental margin type. It has evolved near the leading edge of the American plate in a region where the continental crust varies widely in age, composition, and thickness. Although it has no trench or Benioff zone and has had little historic volcanic activity, the Cascade Range has most of the features associated with volcanic regions near convergent plate boundaries.

The large composite volcanoes of the High Cascades are composed mainly of basaltic andesite and andesite with subordinate amounts of more siliceous calc-alkaline rocks. Most are of the divergent type, having late-stage eruptions of rhyolite or rhyodacite closely associated in time and space with basalt or andesitic basalt. In the central part of the range, where Quaternary activity has been strongest, they are built upon broad overlapping shield volcanoes of high alumina basalt. Although the large cones are topographically imposing, their volumes are small compared to those of the less conspicuous flat-lying basaltic lavas on which they stand.

The volcanoes of the High Cascades have few lavas with reversed magnetic polarities and appear to have been formed entirely within the last million years. They were preceded by a series of earlier volcanic episodes, each of which was characterized by a distinctive spatial distribution, compositional characteristics, and volumetric proportions of rock types. With time, the rocks have declined in volume, average silica content, and concentrations of incompatible trace elements. These changes seem to be related to progressive depletion of lithophile components from the crustal section through which successive batches of magma have risen. No unequivocal link to subduction of oceanic lithosphere has yet been identified.

Introduction

The Cascade Range of western North America was the first andesitic province to be studied in detail, and is still the only orogenic volcanic system for which there is extensive correlated geological and geochemical data. Even here, however, the data are fragmentary and far from adequate. The earliest studies were devoted almost entirely to large composite cones. The classic work of Howel Williams, T. P. Thayer, C. A. Anderson, and others defined the salient geological and petrographic features of the principal volcanoes and provided what still remain some of the most comprehensive accounts of individual eruptive centres. More recent studies have tended to focus on geochemical features of both the Quaternary and Tertiary rocks and have given a clearer picture of the magmatic and tectonic evolution of the system through Cainozoic time.

Although the province is considered a prime example of an active continental margin, it lacks some of the features commonly considered typical of convergent plate boundaries. Most notably, it has neither a trench nor a Benioff zone. In fact, the central part of the province, where Cainozoic volcanism has been most intense, has the lowest seismicity in the western United States. It is also characterized by very

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sparse historic volcanism. Only four volcanoes (Baker, Saint Helens, Hood, and Lassen) have had recorded activity since the region was first settled more than a century ago.

Taken as a whole, however, the record of Cainozoic volcanism is remarkably complete. Thanks to well preserved sections in the Western Cascades and central Oregon and Washington, it is possible to obtain an unparalleled record of the evolution of the province from the earliest Eocene activity through successive episodes to the most recent post-glacial eruptions in the High Cascades. The summary that follows draws heavily on a recent review of current knowledge (McBirney, 1978), and work in progress in both the Quaternary and Tertiary sequences.

Evolution of the Cascade System

The modern volcanic chain that extends from British Columbia to northern California is the most recent of several igneous belts or zones that have followed the Pacific margin of North America since late Paleozoic time (Fig. 1). There is no visible record of Precambrian igneous activity and little evidence for volcanism prior to the last part of the Paleozoic era, but it is clear that there was an important volcanic episode that began during the Permian period and continued well into early Triassic time. Submarine lavas of this age are exposed in northern California, north-eastern Oregon, and northern Washington, and Gilluly (1963) may well be correct in stating that this outpouring of basalt exceeded that of any other period before or after. The nature of the activity was largely oceanic, however, and it is uncertain whether it had much in common with modern orogenic volcanism.

The earliest igneous activity that was clearly orogenic in nature dates from the second half of the Mesozoic era. It was long thought that the plutonic rocks that were emplaced in such large volumes during this episode had little associated volcanism, but detailed studies of contemporaneous sedimentary deposits, notably by Dickinson and his students (Dickinson, 1962, 1970) have shown quite clearly that the batholithic rocks that are so conspicuous today are in fact the roots of a deeply eroded volcanic belt that may not have been very different from the modern High Cascades.

Segments of uplifted plutonic and weakly metamorphosed sedimentary and volcanic units of Mesozoic age are exposed from British Columbia diagonally across the state of Washington into north-eastern Oregon and in isolated windows that extend across central Oregon to connect with the major axis of the Sierra Nevada system in north-western California. This large sigmoidal belt and the embayment it forms near what is now the central part of the High Cascade Range forms one of the major structural features of the crust in the Pacific North-west Hamilton (1969) has proposed that during the period of strongest activity the western Cordilleran axis may have resembled the modern Andes, especially if one reverses post-Cretaceous deformation that is postulated to have accentuated the kink and segmented it into discontinuous blocks. Unfortunately, little is known about the geochemical or geological relations of the volcanic rocks, because most of them have been removed by erosion or are buried beneath a Cainozic cover.

Recent paleomagnetic studies of Eocene rocks of the Oregon Coast Range (Simpson and Cox, 1977) show evidence of up to 60° clockwise rotation and lend support to the postulated oroclinal deformation of the pre-Cascade basement. Various interpretations have been offered for the paleomagnetic data, including large scale motion of plates from various parts of the eastern Pacific margins; however, in at least one instance where detailed magnetic measurements have been made in an area that has been mapped in detail (R. Wells, work in progress), the rotation appears to be confined to small blocks between north-west-trending transcurrent faults with dextral displacement.

Eocene volcanic episodes

The Cainozoic igneous history of western North America has recently been reviewed and summarized by Armstrong (1978), who shows that it

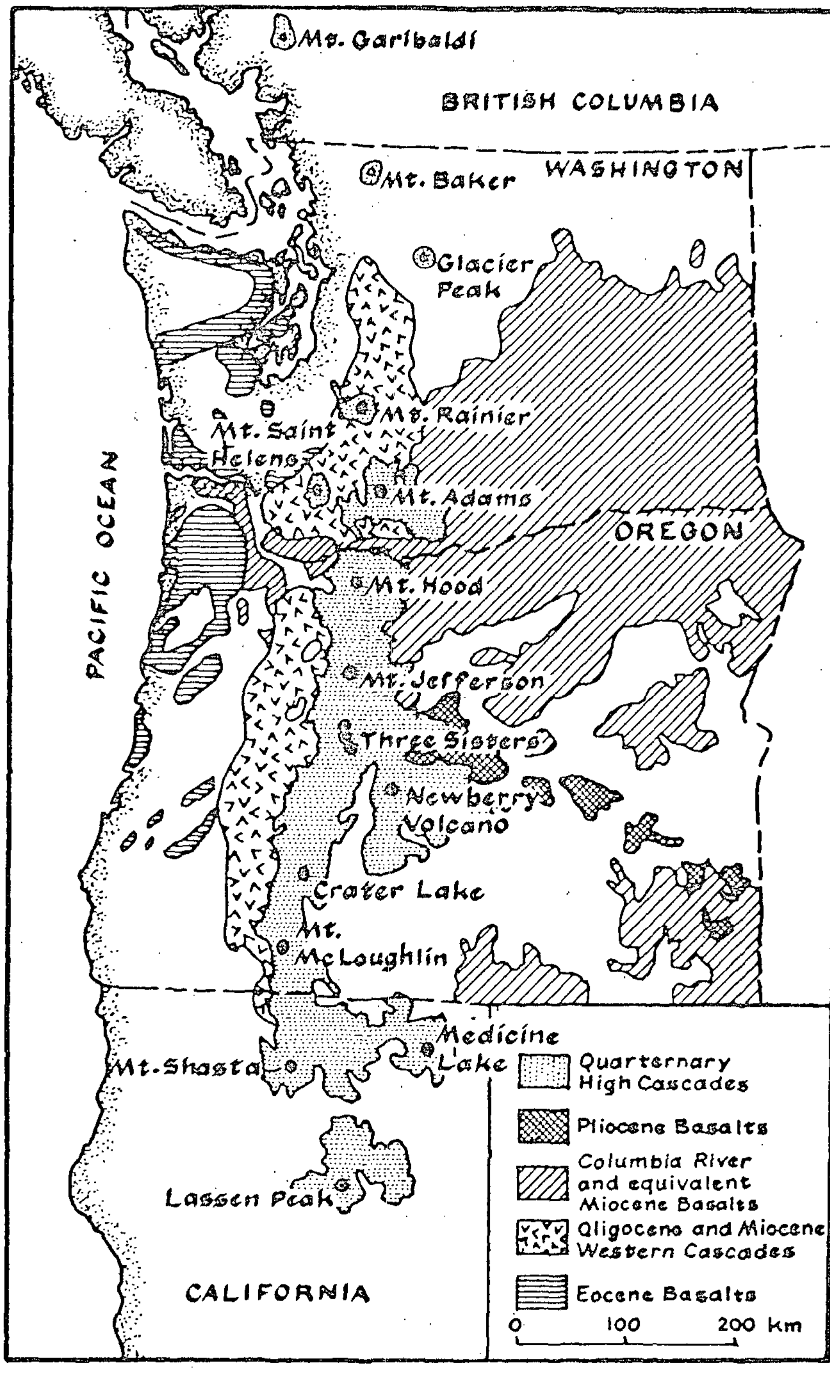


Fig. 1 Generalized map of the Cascade Range and adjacent parts of the northwestern United States

followed a complex pattern of episodic activity that migrated across broad regions. Intense and widespread volcanism began with what Armstrong refers to as the Challis episode. Starting in early Eocene time, it reached its peak between 54 and 44 Ma ago before declining and finally coming to an end near the beginning of the Oligocene era.

The Eocene record of the Pacific North-west can be conveniently divided into early, Middle, and late Eocene stages. Although early Eocene igneous rocks are primarily basaltic and have compositions similar to those of Hawaiian rocks (Snavely *et al.*, 1968), they do not seem to have been erupted in a deep oceanic environment. Lavas and shallow intrusions occur within a thick eugeosynclinal series that accumulated in a shallow subsiding basin, the eastern margin of which was near the present Cascade Range. If there was a trench at this time it must have been far to the west, and although Snavely and Wagner (1963) inferred that andesitic volcanoes were active east of the southern part of the geocyncline, andesitic material has yet to be found in Lower Eocene horizons. Swamp deposits, including coal and shallow estuarine beds, are common, but there are no coarse sediments to indicate a nearby region of high relief. The nature of weathering and vegetation in lacustrine sediments of central Oregon show that the climate of that region was more humid than it has been since the elevation of the Cascade Range brought about more arid conditions in the rain shadow of its leeward side.

A marked unconformity between Lower and Middle Eocene rocks reflects a strong tectonic event that caused extensive folding and possibly thrusting in south-western Oregon (Baldwin, 1965) and a change of sedimentation in the northern part of the province (Rau, 1966). The middle Eocene episode was marked by uplift and erosion of the Klamath Mountain region, together with volcanism, mainly of basaltic character, in localized centres along an axis extending from the partly emergent Coast Range of Oregon along the shallow basin of the Willamette–Puget Sound Depression. At least two volcanic complexes north and south of the present Columbia River erupted tholeiitic rocks that reached moderately high levels of differentiation (Snavely *et al.*, 1965, 1968).

There is sparse evidence that differentiated calc-alkaline rocks began to appear about this time in a belt that was *c.* 160 km wide and extended nearly 1600 km from British Columbia through Washington and into Idaho and western Montana and Wyoming. A separate field developed in central Oregon, and other centres may have been located in the region now covered by Columbia River basalts. Certainly by late Eocene time there must have been a swarm of small volcanoes in these zones. The eruptive centres are marked today by calc-alkaline lavas, tuffs, and subvolcanic intrusions of the Challis and Clarno formations, and by stocks and small batholiths where uplift and erosion have exposed deeper levels, as in Washington and British Columbia.

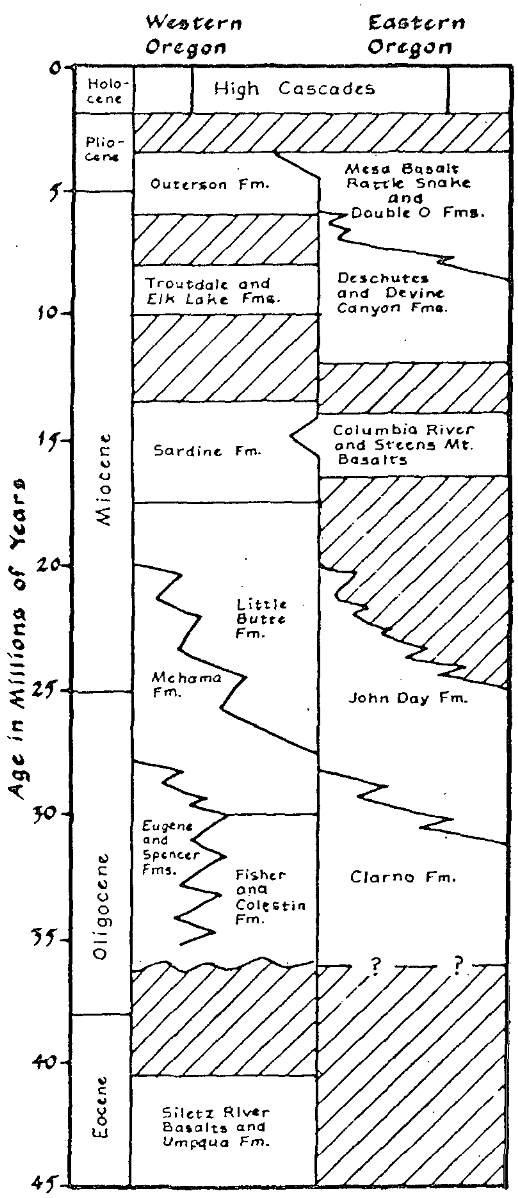
The limited chemical data available indicate that the Challis (F. R. Leavitt, work in progress) and Clarno rocks (Rogers and Novitsky-Evans, 1977) are calc-alkaline in character and include large proportions of andesite, dacite, and rhyolite. In the late stages of activity, they seem to have formed a strongly bimodal association of rhyolite and volumetrically subordinate basalt. The series tend to be distinctly more potassic than those of the High Cascades.

Much of the Oregon Coast Range was emergent by late Eocene time, and the Willamette–Puget Sound Depression had become localized near its present axis. Although there were still scattered central-vent volcanoes in the area of the rising Coast Range, their importance had greatly diminished.

Oligocene to early miocene volcanism

The calc-alkaline volcanism that began in late Eocene time in Washington and central Oregon increased in intensity through the Oligocene epoch and spread westward and southward until it covered a broad zone across most of western Oregon and Washington. It is still uncertain when activity began along the Cascade axis. The oldest andesitic rocks from this region that have been dated by radiometric methods are less than 40 Ma old. (Table 1). Andesitic lavas of the Colestin, Fisher, and equivalent formations in southern Oregon were once thought to have come from late Eocene volcanoes, but dating has shown that they are somewhat younger.

TABLE 1 Stratigraphic column for Quaternary and Tertiary rocks of the Cascade region of Central Oregon



Instead, there is a very marked angular nonconformity separating the Eocene formations from Oligocene calc-alkaline rocks, and the deformation that occurred at that time seems to have coincided with the onset of orogenic igneous activity in the Cascade region.

Certainly by Oligocene time there were many eruptions of andesite and more siliceous rocks from centres in the area of the Western Cascades. Andesitic flows and siliceous tuffs interfinger with Oligocene sediments along the east side and southern end of the Willamette Valley and are abundant in the Oligocene sections of the Clarno and John Day formations east of the Cascades (Hay, 1963; Fisher and Rensberger, 1972). Within the Western Cascade Range, rocks of this age range include the thick Mehama and Little Butte Formations and numerous intrusive bodies that probably represent the eroded remnants of volcanic centres.

The distribution of these centres has not been well defined, but it appears that by the end of Oligocene time small volcanoes were scattered over a broad zone along much of the Pacific continental margin (Fig. 2). In Washington, the locus of activity has been identified in shallow subvolcanic intrusions and associated pyroclastic units near the present Cascade Range, but the full width of the zone cannot be determined there owing to the extensive cover of younger rocks east of the Cascades. In Oregon, Oligocene and early Miocene centres extend from the Coast Range well into central Oregon. In the Coast Range they are marked by subvolcanic intrusions of gabbro and nepheline syenite, while in the Western Cascades and central Oregon, flows, tuffs, and volcanic sediments are associated with vent complexes and shallow stocks, dykes, and sills.

The spatial distribution of the Oligocene rocks is unlike that of modern volcanic belts in that the most alkaline compositions are closest to the ocean. Most of the Oligocene rocks of the Coast Range are alkaline dolerites, gabbros, and nepheline syenites, whereas the main volcanic series of the Western Cascades and central Oregon are strongly subalkaline, and although a few alkaline rocks have been reported from the

John Day formation in central Oregon, they are very subordinate in volume.

As volcanism spread during the Oligocene epoch it tended to become less basaltic and more differentiated with time. The andesites and basalts that dominate the lower parts of the sections in the Western Cascades and make up most of the Clarno formation in the east give way upward to siliceous pyroclastic rocks which, by the end of the episode, reached enormous volumes.

Despite the large volumes of eruptive material, there seem to have been few large volcanoes during this period but rather a scattering of small basaltic and andesitic cones, and a few low-rimmed calderas or broad volcano-tectonic depressions (Walker, 1970). Some of the most voluminous eruptions seem to have come from fissures or from unroofing of shallow intrusions that stoped their way toward the surface. The Coast Range at this time must have formed a peninsula or low island chain, and behind it the Willamette–Puget Sound Depression formed a shallow arm of the sea. There seems to have been no pronounced topographical barrier near the present Cascade axis. Instead, great volumes of tuffaceous debris were deposited in a system of estuaries and shallow basins to form the Eugene formation and equivalent units of the Willamette Valley and the lacustrine beds of the John Day formation in central and eastern Oregon. Coarse detritus and deep erosional channels are notably rare, and the relief on the volcanic landscape could not have been great.

The broad distribution of volcanism during this episode provides an excellent opportunity to compare the compositions of rocks erupted at differing distances inland along a section normal to the continental margin. The total volume of erupted material and the proportions of siliceous pyroclastic rocks increase markedly inland; in the same direction, rocks at the same level of differentiation become richer in K, Rb, Zr, Sr, Ba, and La/Sm and poorer in Ni and Cr. The lavas erupted along the western margin are unusual in that they contain few phenocrysts and seem to have been very hot and fluid when poured out on the surface. They are somewhat more Fe-rich and tholeiitic than the younger calc-alkaline suites (Table 2).

Mid-miocene (columbian) volcanism

An episode of faulting, uplift, and erosion occurred during the later part of early Miocene time throughout much of central Oregon. There is a marked erosional non-conformity at the top of the John Day formation and in places erosion cut down well into the underlying Clarno rocks before the mid-Miocene basalts of the Columbia River Group were laid down. The intensity of this disturbance seems to have diminished westward, because it is not conspicuous in rocks immediately east of the High Cascades (Peck, 1964) or in the Western Cascades (Peck *et al.*, 1964). A general decline in the intensity of volcanism about this same time is reflected in a relative scarcity of igneous rocks with ages of between 20 and 16 Ma. Following this interval, however, volcanism increased greatly. In fact, the mid-Miocene, or Columbian episode, as it is sometimes called, was by far the most important igneous event to occur in the Pacific Northwest during the Cainozoic era.

Rocks of this age in the Cascades have been assigned to the Sardine Formation of Thayer (1937) and constitute what is probably the thickest and most voluminous assemblage of andesites in the region. If one adds to the Sardine Formation the flood lavas of the Columbia River and Steens Mountain Groups and the calc-alkaline rocks of the Strawberry Mountains, all of which were erupted in central and eastern Oregon and Washington during the same time interval, the total volume of mid-Miocene rock becomes enormous. This large volume is even more remarkable when one considers the brief time-span in which it was erupted.

Volcanic centres of mid-Miocene age have been relatively well delineated along two belts, one trending slightly east of north along the Western Cascade axis and possibly connecting with a similar belt that curves toward the south-east through northern California and south-western Nevada (Noble, 1972), and a second shorter belt that is marked by three middle to

TABLE 2 Weighted average compositions of Cainozoic volcanic rocks of the Oregon Cascades and northern California

	Quaternary rocks	Quaternary rocks	Pliocene rocks	Middle and Upper Miocene rocks	Oligocene–Miocene Rocks
	Northern California	Central Oregon			
Average composition (in wt %)					
SiO_2	52.2	52.7	52.7	57.3	62.4
TiO_2	1.2	1.4	1.3	1.1	0.9
Al_2O_3	18.0	17.4	17.3	16.6	15.7
ΣFeO	9.6	9.1	8.6	7.4	6.1
MnO	0.1	0.1	0.1	0.1	0.1
MgO	5.5	5.3	5.6	3.7	2.3
CaO	9.1	8.4	8.7	6.7	5.3
Na_2O	3.2	3.8	3.5	3.5	3.4
K_2O	0.9	0.9	0.9	1.3	1.7
P_2O_3	0.2	0.3	0.2	0.3	0.2
Total	100.0	99.4	98.9	98.0	98.1
No. of analyses and percentage of rock types by volume (in parentheses)					
Basalt	7 (69)	33 (85)	17 (90)	20 (39)	6 (10)
Andesite	22 (29)	112 (13)	76 (9)	99 (41)	25 (45)
Dacite–rhyolite	35 (2)	31 (2)	6 (1)	17 (20)	10 (45)
Total volume of rocks (in km³)	3095	4600	2150	24 850	> 10 000

late Miocene volcanic centres trending northeast through the Strawberry Mountain complex and other igneous centres in east-central Oregon (Robyn, 1977) (Fig. 2). Of these two chains, that of the Western Cascades was the most extensive and produced the largest volume of calc-alkaline rocks. Its axis is marked by stocks, mainly of quartz diorite, and by broad aureoles of hydrothermal alteration and mineralization. The forms of the cones can be inferred from the lithologic zones that reflect the conditions under which lavas and pyroclastic rocks accumulated on the slopes and lower flanks of large composite volcanoes. These centres seem to have been the first to have the form and alignment that is conventionally associated with andesitic belts. They probably resembled volcanoes of the modern High Cascades, except that the presence of shallow water sediments between them indicates that the belt was a chain of volcanic islands or a broad shelf area, at least during its early stages of development.

There is surprisingly little correlation of mid-Miocene units on opposite sides of the High Cascades. Despite their great thickness in the Western Cascades, andesitic rocks are scarce, or absent, along the eastern base of the modern range. A few thin flows of basalt within the Sardine Formation have been correlated with the Columbia River Group to the east (Peck *et al.*, 1964; White and McBirney, 1978) and indicate that tongues of flood lavas flowed between the andesitic cones, but it is difficult to visualize the topographic configuration that could account for the limited interfingering of two adjacent units of such great thicknesses. The problem is made more difficult by the shallow level of erosion and the extensive cover of younger rocks that limit exposures on the east side.

Most of the products of mid-Miocene volcanism in the Western Cascades were andesitic. Siliceous pyroclastic rocks are much less important than they were in the preceding episode, and basalts were still quite subordinate (Table 2). The relationship, if any, between this andesitic volcanism and the great outpouring of flood lavas of the Columbia River Group has never been explained. The same brief episode during which these large volumes of volcanic rocks were erupted was also marked by strong activity in Central America, the south-western Pacific, and other parts of the circum-Pacific system (McBirney *et al.*, 1974, Kennett *et al.*, 1977).

Late miocene (andean) volcanism

The Columbian episode declined sharply c. 13–14 Ma ago and was followed by moderately strong deformation throughout much of the Pacific North-west. Strong faulting and tilting occurred east of the Cascade Range where an important angular unconformity separates Pliocene rocks from the underlying older units. In the Cascade region, broad folds developed along axes that closely parallel the trend of the earlier mid-Miocene volcanoes.

A brief late Miocene pulse of activity, dated *c.* 9–10 Ma ago, has recently been recognized in the Western Cascades (McBirney *et al.*, 1974) and appears to have been synchronous with strong volcanism elsewhere in the circum-Pacific region, especially the Andes. The rocks have only been separated from the older Sardine Formation in a few areas where detailed studies have been carried out. They appear to have been erupted from small cones around the lower flanks of the large eroded remnants of mid-Miocene volcanoes and from scattered vents east of the Cascades. Known centres in the Cascades are too few to permit an interpretation of the distribution of vents or their relationship to regional conditions. In central Oregon, however, there appears to be a systematic migration of late Miocene rhyolitic eruptions toward the Cascades (G. W. Walker and N. S. MacLeod, personal communication). In addition, rhyolitic and dacitic ignimbrites and scattered basaltic lavas were erupted throughout much of central and eastern Oregon (Walker, 1970). Taken as a whole, the episode was characterized by andesitic and basaltic lavas in the Cascades and dominantly silicic ignimbrites and domes toward the east.

Pliocene (fijian) volcanism

Kennett *et al.* (1977) have applied the name Fijian to the important volcanic episode that occurred between c. 3 and 6 Ma ago. The name was taken from the islands in the south-western Pacific where the episode was first established by systematic dating, but volcanism was widespread at this time throughout much of the circum-Pacific region. Rocks of this episode are widespread in the Cascade Range, central Oregon, northern California, and the Basin and Range Province, but it is often difficult to distinguish them from Pleistocene and Holocene units, because they are only moderately affected by weathering and erosion (Fig. 1).

Activity in Oregon during this period produced mainly basaltic lavas and rhyolitic domes and ignimbrites (Fig. 2). Small monogenetic cones and thin but extensive flows of basalt broke out over a broad region extending from the western side of the Cascades across central Oregon almost to the Idaho border. Rhyolitic ignimbrites were also erupted from centres east of the Cascades, and the chain of rhyolitic domes that began to develop in late Miocene time continued its westward migration toward the Cascade Range. Another region of basaltic and rhyolitic activity developed in southern Idaho and migrated eastward along the Snake River Plain toward Yellowstone.

Andesites seem to have been subordinate to basalt and rhyolite, and there were no conspicuously large composite cones near the axis of the Cascades. By this time most of the large Miocene volcanoes had probably been levelled by erosion. Coarse andesitic debris is widespread in alluvial and lacustrine deposits along the eastern side of the Cascades where it was deposited in pediments and a number of subsiding basins.

Quaternary (cascadian) volcanism

The recent episode of volcanism that has been responsible for the familiar volcanoes of the modern High Cascades has been studied in greater detail than any other Cainozoic period, but even today much remains to be learned about the volcanoes and their relations to the system as a whole. This last period of activity, from which the Cascadian episode takes its name, followed closely and, in places, merged with the preceding Pliocene episode. Its main feature was a marked narrowing of the focus of volcanism to form a well defined chain of large composite cones extending from British Columbia to northern California (Figs. 1 and 2).

The earliest Pleistocene activity resembled that of the preceeding Pliocene episode in that it was characterized by basaltic cones, flows, and low overlapping shields. With time, activity became more localized in persistent centres from which progressively more differentiated magmas were discharged. Most of the large andesitic cones that form the crest of the High Cascades began to rise during Pleistocene time *c.* 1 Ma ago and reached their present elevations by rapid growth during a brief period of intense activity. The fact that few of the lavas have reversed magnetic polarities, even in the lowest levels of deeply glaciated cones, indicates that by far the greatest volumes must have been discharged since the present period of normal magnetic polarity began about 670 ka ago.

Block-faulting occurred concurrently with volcanism in the central Cascade Range and resulted in uplift and westward tilting of the Western Cascades. At the same time, the basement below the active volcanoes of the High Cascades began to subside to form a shallow graben, much of which has been filled by the products of Quaternary volcanoes (Fig. 3). Depression of the Cascade graben has been most pronounced in the central Cascades where volcanism has been strongest; it dies out toward the north and south where individual volcanoes are large but widely spaced, and the total volume of Quaternary volcanic rocks is small.

The topographically imposing volcanoes of the High Cascades give the impression that andesite is the dominant rock type in the modern range. In places this is probably true, but if one considers the total volume of rocks produced in the system as a whole, andesitic cones are seen to account for a very subordinate amount of the erupted volumes. The proportion of andesite is high only in those parts of the chain where the total volume of Quaternary rocks is small, namely in Washington and northern California. In one part of the central Oregon Cascades where absolute volumes have been estimated (McBirney *et al.*, 1974), it has been found that basaltic lavas beneath and between large andesitic cones account for *c.* 85 per cent of the total volume of Quaternary rocks. Glaciated shield lavas were found to total *c.* 1282 km^3, while large composite cones in the same area account for *c.* 189 km^3, and the very recent scoria cones and lava flows amount to *c.* 55 km^3. Unfortunately, most geological and petrological studies have been concentrated on the high cones, and the great volume of underlying rocks and smaller volcanoes have been largely ignored.

The Quaternary rocks of the High Cascades have most of the petrographic and petrochemical features considered typical of the calc-alkaline rocks of modern continental margins. Almost all rocks, with the exception of the most basic basalts and the most siliceous rhyolitic obsidians, are strongly porphyritic and rich in plagioclase. Basalts commonly contain up to *c.* 20 per cent of olivine phenocrysts. The olivine may have minute inclusions of reddish brown spinel and rarely shows a reaction relationship to the groundmass. Olivine is not uncommon as phenocrysts in basaltic andesites and andesites, but it contains few, if any, inclusions of spinel and is normally corroded and rimmed with pyroxene. Titaniferous magnetite, although abundant in the groundmass of almost all rocks, is seldom important as phenocrysts. Most andesites contain two pyroxenes, augite and

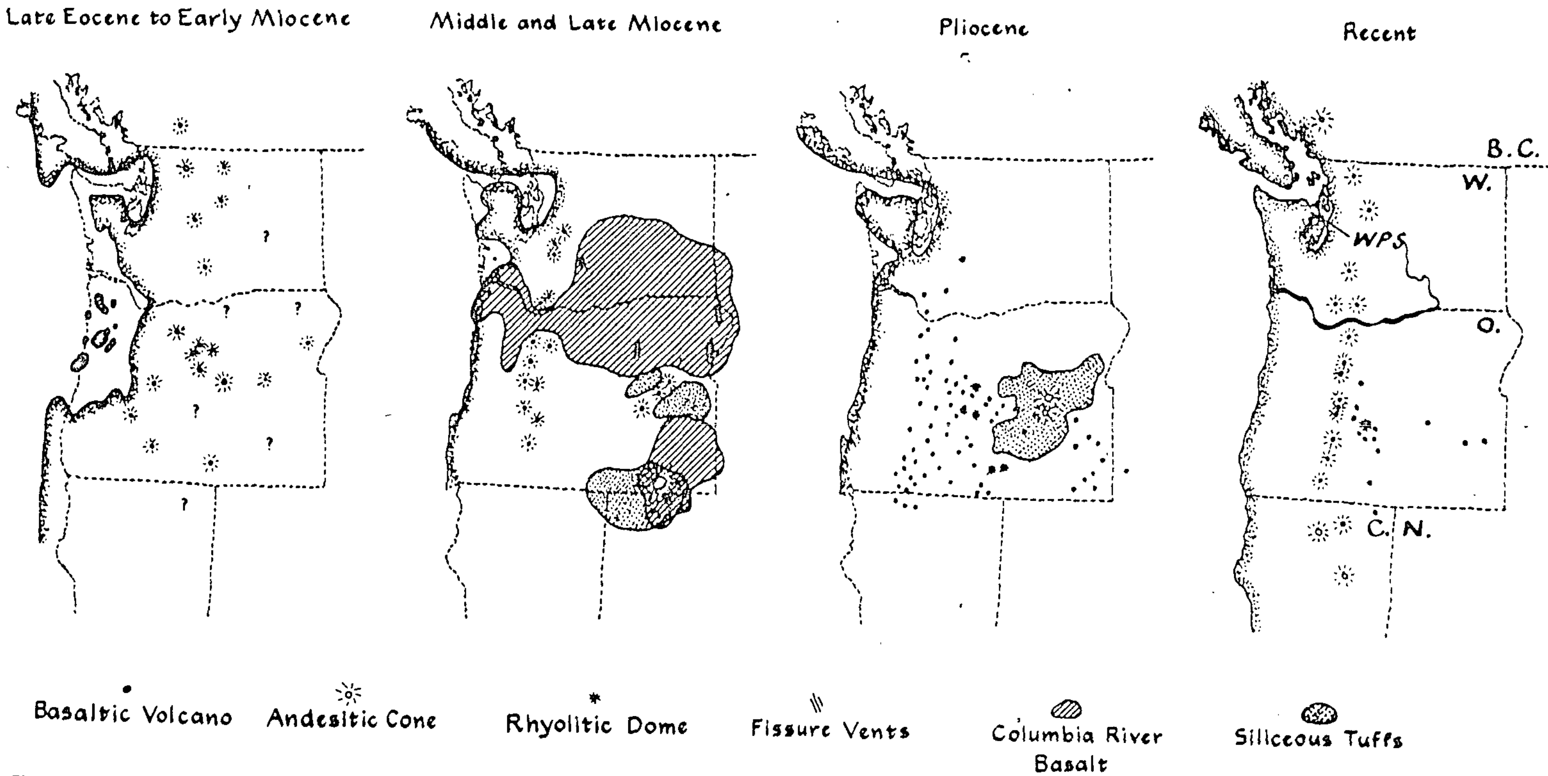


Fig. 2 Paleogeographic reconstruction of the Pacific North-west during Cainozoic time, compiled from various sources, including Snaveley *et al.* (1968) and Armstrong (1978) (from McBirney, 1978). National and state boundaries are indicated by broken lines as indicated on the 'Recent' reconstruction with BC = British Columbia (Canada), W = Washington, O = Oregon, C = California, and N = Nevada; WPS = Willamette-Puget Sound

TABLE 3 Average compositions of Quaternary volcanic rocks of the central Oregon Cascades

	Basalt, 43 Analyses (<53.5% SiO_2)		Basaltic andesite, 57 Analyses (53.5–57% SiO_2)		Andesite, 56 Analyses (57–63% SiO_2)		Dacite, 16 Analyses (63–68% SiO_2)		Rhyolite, 15 Analyses (>68% SiO_2)	
	(wt%)	(S.D.)	(wt%)	(S.D.)	(wt%)	(S.D.)	(wt%)	(S.D.)	(wt%)	(S.D.)
SiO_2	51.1	1.84	55.4	0.91	60.0	1.72	64.9	1.78	71.6	2.47
TiO_2	1.4	0.33	1.0	0.17	0.9	0.16	0.7	0.22	0.3	0.13
Al_2O_3	17.3	0.99	17.9	0.72	17.4	0.64	16.2	0.42	13.9	0.65
ΣFeO	9.4	2.40	7.6	0.79	6.4	0.79	4.7	0.83	2.4	0.57
MnO	0.2	0.02	0.1	0.1	0.1	0.03	0.1	0.03	0.1	0.02
MgO	6.1	2.03	4.6	0.92	2.8	0.73	17.	0.56	0.5	0.34
CaO	8.9	0.78	7.5	0.78	6.1	0.75	4.4	0.99	1.7	0.36
Na_2O	3.6	0.56	3.9	0.29	4.3	0.34	4.5	0.56	4.5	0.43
K_2O	0.8	0.24	0.9	0.22	1.2	0.33	1.6	0.33	3.0	0.35
P_2O_3	0.3	0.12	0.2	0.07	0.2	0.06	0.2	0.08	0.1	0.05

hypersthene, which vary little in composition throughout the series. Hornblende is much less common. It occurs as oxidized relicts in a few andesites but is a common phase only in dacites and rhyolites. Plagioclase is by far the most conspicuous phase among the phenocrysts throughout the series. It normally has very complex zoning that may differ from grain to grain, even in a single thin section. Its composition is also varied but is normally in the range of sodic labradorite to calcic andesine. The groundmass plagioclase shows a somewhat wider range of composition between rocks of differing silica contents but is rarely more sodic than oligoclase.

The chemical compositions of the principal Quaternary rock types in the central Oregon Cascades are given in Table 3.

In recent years, several Quaternary High Cascade volcanoes have been examined in considerable detail, but much of this work is still incomplete, and there are few places where the entire volcanic and petrological development of a large cone can be traced. The most complete data are probably those for Mount Jefferson (Thayer, 1937; Walker *et al.*, 1966; Greene, 1968; Condie and Swenson, 1973; Sutton, 1974; White and McBirney, 1978). Four stages of activity have been recognized (Fig. 4(a)). The earliest Pleistocene eruptions formed a broad base of basaltic shield lavas on which the main cone was then built during two separate stages of andesitic activity. Finally, in very recent time, small flows of basalt were discharged from satellite vents on the lower flanks of the main cone. There was a general increase in the silica content through the three main stages of growth and a steady decline in the volumes of erupted rocks, but the flank eruptions of the last stage reverted to a more basic composition similar to that of the Pleistocene shield lavas. The magma of each of the four stages had its own distinctive

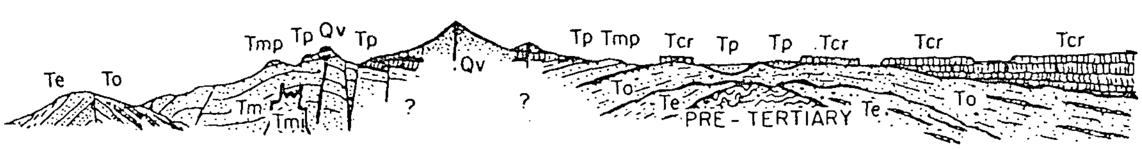


Fig. 3 Schematic cross-section through the central Oregon Cascades showing known and inferred structural and stratigraphic relations. Ages of units are designated as follows: Te = Eocene, To = Oligocene, Tm = Miocene, Tmp = Mio-Pliocene, Tp = Pliocene, Qv = Quaternary. Tcr indicates Columbia River Basalt, and Tmi refers to subvolcanic stocks of Miocene age

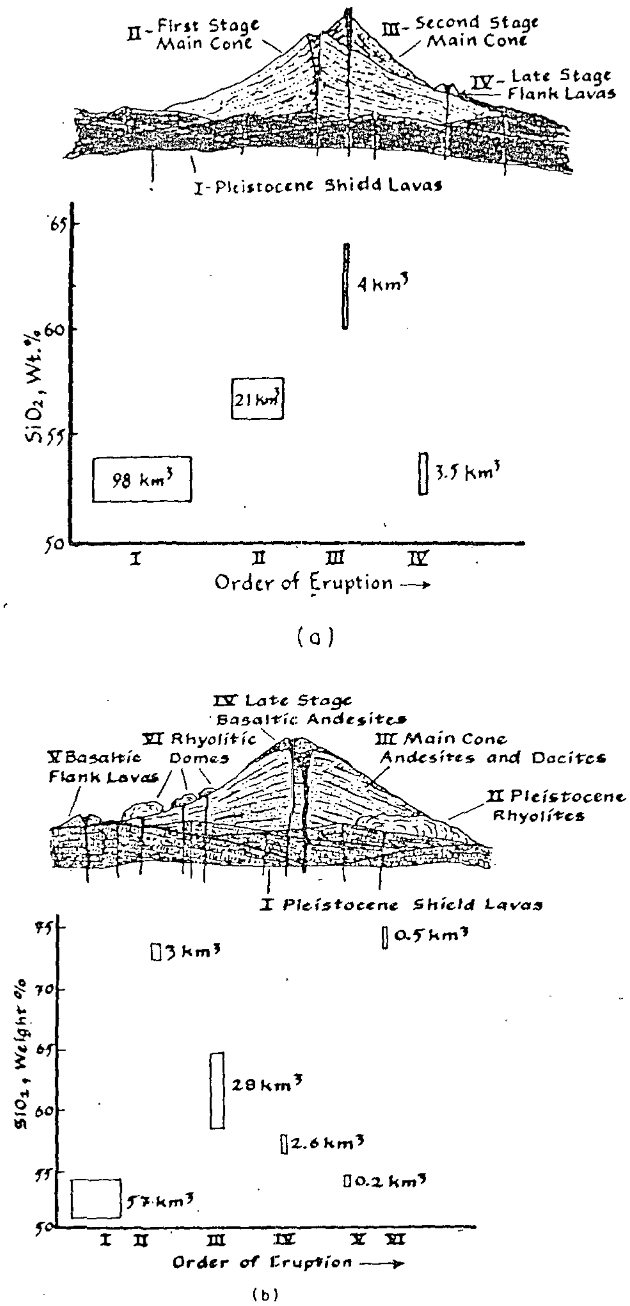


Fig. 4 (a) The Quaternary evolution of Mount Jefferson included four main stages, each of which was characterized by distinctive rocks. Volumes of rocks in each stage are shown by the relative areas of rectangles in the lower diagrams. The mid-point on the vertical dimension of the rectangle is placed at the mean value of SiO_2 for the rocks of that stage, and the vertical length of the edge indicates one standard deviation for the silica value. (b) The Quaternary evolution of the Three Sisters complex resembles that of Mount Jefferson but is characterized by more siliceous rocks, especially in the final stage when the magma became strongly divergent

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Similar patterns of development have been followed by most of the other large Quaternary cones, but in many places late-stage eruptions have produced not only basaltic rocks but rhyolitic or dacitic domes and pumice as well. This pattern in which compositions evolve through andesite and then diverge into more or less contemporaneous basalt and rhyolite in the latest stages of activity is most pronounced in the southern and northern parts of the chain.

At the Three Sisters (*see* Fig. 1), for example, the main andesitic cones are ringed with domes of rhyolitic obsidian and, at lower elevations, by contemporaneous basaltic scoria cones (Fig. 4(b)). Studies by J. Clark (work in progress) have shown that the divergent late-stage magmas were derived from the same parent, possibly by gravitational stratification of a shallow body of magma. A similar pattern is seen at Mount Mazama (Crater Lake) where siliceous domes and pumice have erupted from vents on the upper flanks of the main andesitic cone while basalt and andesitic basalt were discharged at lower elevations. Clear evidence of a graded magma is seen in the products of the climatic eruption that led to formation of the caldera. Ritchey (1980) has shown that the upper siliceous magma responsible for the large volumes of rhyolitic pumice discharged during the main stages of the Plinean outpourings overlay a crystal-rich zone of more mafic composition that was tapped at the close of the eruption. Geochemical and petrological evidence indicates that the two compositions evolved by gravitational stratification of an initially homogeneous intrusion.

Summary of geological development of the Cascade system

The foregoing descriptions have been very brief and are far from complete, but it is apparent even from this short summary that the Cascade system has evolved to its present form through a varied succession of igneous and tectonic events and that the setting of volcanism today is by no means characteristic of that in earlier periods.

Calc-alkaline volcanism first appeared around the close of the Eocene epoch east of the present Cascade axis and gradually spread across a broad region during Oligocene and early Miocene time. A well defined line of composite volcanoes did not develop until the mid-Miocene Columbian event, and following that episode there was no new chain of large andesitic volcanoes until the modern High Cascades began to rise *c.* 1 Ma ago.

Tectonic disturbances occurred at several times and in different regions. The strongest deformation seems to have occurred in the southern Coast Ranges around the end of middle Eocene time, but conspicuous faulting and uplift also took place east of the Cascades shortly before the mid-Miocene volcanic episode and again shortly before the late Miocene and Pliocene episodes. Basin and range faulting extended into central Oregon toward the end of Pliocene time and has continued down to the recent past.

Trends of Magmatic Evolution

Several aspects of the Cainozoic activity stand out when the sequence of igneous episodes is viewed as a whole. Although the volumes of volcanic and intrusive rocks produced during the early episodes are difficult to estimate, they were certainly much greater than those of more recent times. There has been a somewhat irregular decline of volcanism with each successive episode since the mid-Tertiary pulses, which were by far the most intense and widespread to occur anywhere near the present Cascade axis. The time span during which most of the Oligocene and early Miocene rocks were erupted seems to have been of the order of 10 Ma, but the mid-Miocene episode was much shorter, possibly only 2 or 3 Ma. Hiatuses in which there was little or no volcanism seem to have separated each of the subsequent volcanic episodes down to the present.

The proportion of basaltic rocks has increased steadily with time (Table 2). The Oligocene–early Miocene episode produced the largest volume of siliceous rocks, mainly rhyolite and dacite; andesite was the dominant rock type produced in the Cascades during the mid-Miocene (Columbian) episode, and since that time basalt has outweighed all other rock types combined. In the modern High Cascade chain, andesite is important only in the southern and northern parts of the chain where the intensity of Cainozoic volcanism has been relatively mild. Elsewhere, there are large composite cones composed largely of andesite, but they constitute a relatively small part of the total erupted volume.

Knowing the relative proportions of the different rock types in each age group and the average compositions of the individual members of each series, it is a simple matter to calculate the average compositions of volcanic rocks produced during successive igneous episodes. This has been done for the central Oregon Cascades by White and McBirney (1978) who obtained the results shown in Table 2. For purposes of comparison, data are also shown for Quaternary rocks of northern California.

The most notable feature of these averages is the decline of silica and potash with time. The Na content is remarkably uniform, mainly because the concentration of that element in basalts has increased by an amount that balances the increased proportions of mafic rocks. Similarly, the average of Quaternary rocks in the central Oregon Cascades does not differ markedly from that of northern California, even though dacites and rhyolites are much more abundant in the southern part of the chain. The reason for this apparent inconsistency lies in the fact that the basalts of northern California tend to be more basic than those of central Oregon.

As the proportions of rock types changed with time, the nature of the individual members of the suites also seem to have evolved in a systematic way (Fig. 5). If basalts of each of the major eruptive episodes are compared, they are seen to become progressively more sodic with time. The younger rocks have lower Fe/Mg ratios, and they are progressively depleted in certain trace elements, notably Zr, Rb, and REE. The rate of decline of these incompatible elements in each successive suite can be correlated directly with the amount of volcanism that has occurred in a given part of the Cascade chain (White and McBirney, 1978). The relationship is shown most clearly in Rb; in those regions where there has been a large amount of Tertiary igneous activity, the modern rocks are more depleted in this element than are those erupted in regions where the magnitude of earlier volcanism was less. At the same time, the isotopic ratio of Sr in basaltic rocks of the central Oregon Cascades has declined from *c.* 0.7035 to *c.* 0.7030.

Relations such as these indicate that the source of Cascade magmas has been somewhere in the mantle, possibly between the postulated subduction zone and the overlying continental lithosphere, but that a multistage process is required to explain all the temporal and compositional variations in the system as a whole. The decline of Fe contents and the increase of Na with time can be explained by postulating that the depth at which the basalts last equilibrated with the mantle has increased with time. Experimental studies of the compositions of melts in equilibrium with crystalline phases at various pressures (Kushiro, 1973; Mysen, 1974; Osborn and Watson, 1977) have shown that mantle liquids probably become richer in Na and poorer in Fe with increasing depth and pressure. This increase could come about as a result of progressive thickening of the lithosphere, both by accumulation of eruptive rocks at the surface and by underplating of the brittle layer with a solid residue from which the liquid fraction of each batch of magma was separated as it rose toward the surface.

The progressive depletion of lithophile elements with time may take place at the source or in the lithosphere through which the magma must pass *en route* to the surface. Progressive melting of a single source in the mantle could account for the observed decline of volumes, Fe/Mg ratios, silica, K, and other lithophile components, but similar variations might also result if successive batches of magma pass through the same section overlying the source and deplete the rocks of components that are selectively fractionated into the liquid. The first liquid to pass through a given section would

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scavenge more of these elements than successive ones following the same path.

The only way to discriminate between the individual effects of these two processes is to compare rocks from regions having different crustal structures and magmatic histories. Table 4 and Fig. 6 provide comparative data for Cainozoic lavas of several different regions and eruptive episodes. The most notable relations are, first, a marked increase in the concentrations and ranges of abundances of lithophile elements in rocks of the same differentiation index erupted at increasing distances toward the continental interior and, second, the decline in the concentrations of the same elements in rocks erupted in the same area over the course of time.

Similar increases of the concentrations of lithophile elements observed toward the interior of other provinces have been attributed to either an increasing depth of an inferred subducted slab or, alternatively, to the increasing thickness of crustal rocks from which rising magma can scavenge elements that are strongly partitioned into the liquid phase. The fact that the range of values increases along with the average abundance is in accord with the direct correlation found between these factors and crustal thicknesses (Condie and Potts, 1969; McBirney, 1976). If the high concentrations were more uniform in rocks of the same differentiation index, they could be explained as the result of equilibrium fractionation during melting or crystallization, but the fact that they vary so widely implies that the enrichment process is due, in large part, to the vagaries of contamination and assimilation.

This same conclusion could be reached from a comparison of rocks erupted in the same area over a period of two or more magmatic episodes. The fact that the abundances decline steadily with time shows that they cannot be attributed to a steady state process of subduction but are

TABLE 4 Selected representative data on orogenic igneous rocks of the Cascade Province compiled from various sources, including Condie and Swenson (1973), White and McBirney (1978), Rogers and Novitsky-Evans (1977), Rogers and Ragland (1980, and personal communication), and unpublished data from work in progress. Data 1A come from Oligocene to early Miocene rocks of the Calapooya Valley on the western edge of the Western Cascades. 2A, 2B, and 2C come from Oligocene–early Miocene, middle to late Miocene, and Quaternary rocks respectively in the area of Mount Jefferson in the central Oregon Cascades. 3C comes from the area around Mount Rainier in Washington, and 4A is from the early Tertiary Clarno Formation of central Oregon. DI = Si/3 − Mg − Ca + K

	1A	2A	2B	2C	3C	4A
Volume (km^3) in 2000 km^2	> 6000	> 10 000	27 000	4600	1380	
Percentages of rock types						
Basalt	32	10	39	85	33	
Andesite	59	45	41	13	60	
Dacite–rhyolite	39	45	20	82	7	
Weighted average SiO_2	56.1	62.4	57.3	52.7	58.1	
Lithophile elements at DI = 5						
K_2O (wt %)	1.2 ± 0.5	2.2	2.1	1.4	1.7	1.2 ± 0.6
Rb (p.p.m)	23 ± 10	46 ± 16	36 ± 10	16 ± 5	46	50 ± 21
La/Sm	3.7	2.9	3.45	3.92	3.95	—
Zr (p.p.m.)	163 ± 20	263 ± 35	205 ± 20	120 ± 20	174	235 ± 80
Ba (p.p.m.)	225	462	405	360	338	465 ± 120
Included elements at DI = 1.0						
Ni (p.p.m.)	17	22	70	65	55	66 ± 24
Cr (p.p.m.)	18	42	35	85	74	390 ± 10
$^{87}Sr/^{86}Sr$	0.7035	0.7035	0.7032	0.7030	0.7038	

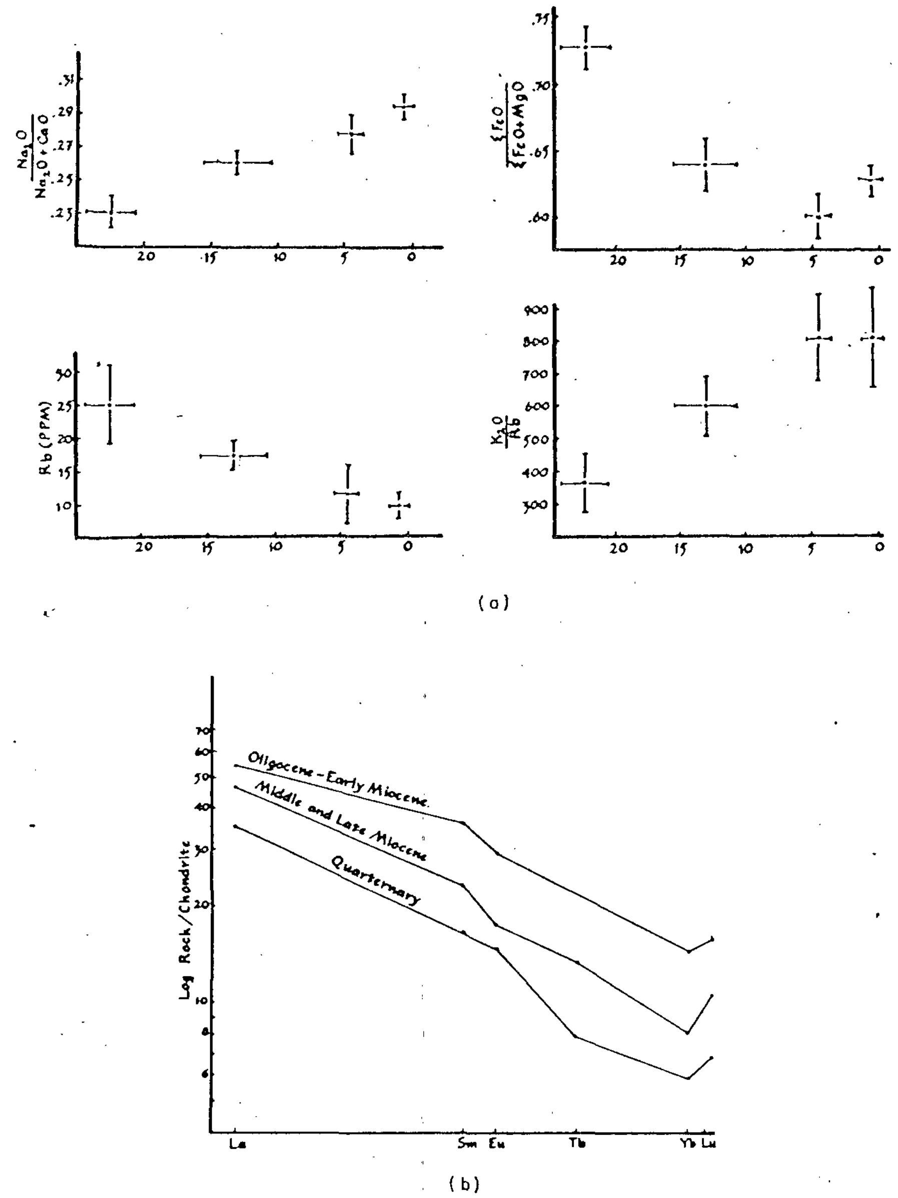

Fig. 5 (a) Variations of $Na_2O/(Na_2O + CaO)$, $\sum FeO/\sum(FeO + MgO)$, Rb, and K_2O/Rb with time in basaltic rocks of the central Oregon Cascade Range. Error bars show one standard deviation in chemical data and the range of radiometric dates for the same rocks. (b) Mean abundances of REE in radiometrically dated samples from the central Oregon Cascades. Data are normalized to the mean silica content of the middle and late Miocene group (58 per cent). (From White and McBirney, 1978)

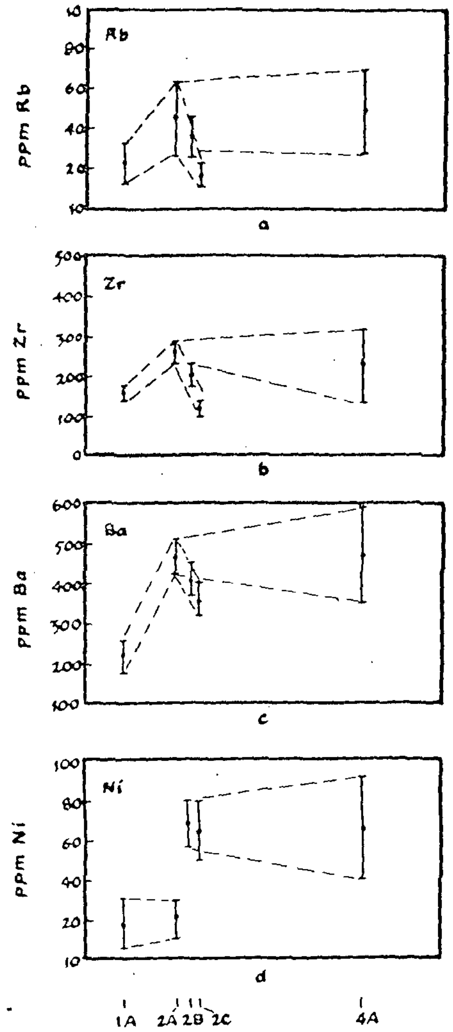

Fig. 6 Abundances of Rb, Zr, Ba, and Ni in rocks of differing geological settings and ages in central Oregon. Horizontal scale is proportional to the east–west distance from the continental margin; numbers and letters on the scale identify the groups according to the key in Table 4. *See* text for discussion

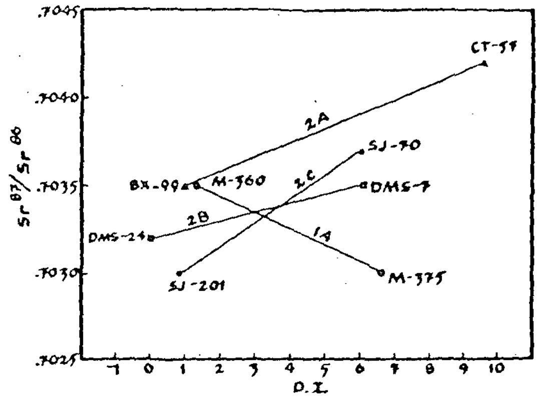

Fig. 7 Isotopic ratios of Sr in rocks of differing ages and differentiation indices. 1A, 2A, 2B, and 2C correspond to the groups of the same designation in Table 4. Determinations by R. L. Armstrong. *See* text for discussion

more probably the result of progressive depletion of mobile elements in the crustal rocks through which the magmas must rise. If the declines were caused by depletion of a fixed source in the mantle, the incompatible elements would be so strongly fractionated into the first liquid that an abrupt rather than gradual decline would be observed in successive melts from the same source.

A further insight into these processes can be gained from comparisons of the abundances of a strongly compatible element, such as Ni, in the same groups of rocks just considered. Because Ni has a high distribution coefficient in olivine, its concentration in liquids is very sensitive to fractionation of that mineral and reflects the conditions under which the magma last equilibrated before erupting.

The patterns of variations of Ni in space and time are quite marked (Fig. 6(d)). The spatial relations show that the abundance of this element in early Cainozoic basalts increases sharply toward the interior of the continent. With time, it also increases by approximately the same amount where successive igneous episodes have taken place in the same area. Unlike the lithophile elements, however, Ni does not have a continuous range in rocks at the same stage of differentiation (DI = 1.0). It tends to have one of two separate average abundances, and we find little or no overlap between the two groups. Tholeiitic basalts contain *c.* 20 ± 10 p.p.m. Ni, whereas calc-alkaline basalts, regardless of their age, contain *c.* 65 ± 25 p.p.m. The limited data we have on very primitive basalts of both types of suites indicate that Ni contents converge on a common value of over 100 p.p.m. at differentiation indices below *c.* -1.0. Hence, both the calc-alkaline and tholeiitic series could be derived from a similar parental composition, but the latter would evolve through fractionation of olivine, whereas the calc-alkaline series does not seem to have crystallized a mineral that strongly depletes the liquid in Ni.

Several factors could influence the degree of fractionation of olivine and hence the Ni contents of these basalts. Load pressure, water pressure, oxidation state, and silica and alkali contents of the liquid have all been shown to affect the stability field of olivine. The explanation that seems most consistent with the relations we observe is one based on a difference in water content and the relative roles of olivine and amphibole in early stages of differentiation. The amount of Ni fractionated from primitive basaltic magmas would be greatly reduced if amphibole replaced olivine as a liquidus phase. Numerous earlier workers have advocated amphibole as a key mineral in the evolution of calc-alkaline suites, and the increase in Ni contents which we find between the tholeiitic and calc-alkaline rocks of the Cascade system is consistent with this hypothesis.

When considered in terms of the geological setting of the various igneous centres and the patterns of variations of lithophile elements outlined in the preceding pages, the abrupt transition from Ni-poor tholeiitic to Ni-rich calc-alkaline basalts in space and time can be directly related to the nature and thickness of the crust and to the conditions under which olivine gives way to amphibole as an important liquidus phase. The boundary between the stability regimes of these two minerals must become deeper as the amphibolitic continental lithosphere thickens with time and distance from the continental margin.

There is ample evidence that the nature of the crust through which the Quaternary lavas of the High Cascades have risen had an important influence on the volumes and compositions of erupted rocks. Volcanoes at the southern and northern ends of the chain stand on thick continental crust (Dehlinger *et al.*, 1965) and have relatively small total volumes but large proportions of andesite; they also tend to be more potassic. The average K_2O content (normalized to 60 per cent SiO_2) for representative volcanoes in the northern, central, and southern regions are

Rainier (10 analyses)	1.66 per cent K_2O
Hood and Jefferson (41 analyses)	1.43 per cent K_2O
Lassen and Shasta (10 analyses)	1.59 per cent K_2O

Because the volumes also differ, the K_2O contents tend to vary directly with the proportion of andesite in each part of the chain.

The isotopic ratios of Sr also lend support to this interpretation. The lavas of volcanoes built on thick continental crust are somewhat more radiogenic than those of the central Oregon Cascades, where the continental crust is relatively thin, and, with time, the basic rocks of successive series have progressively lower ratios (Table 4, Fig. 7). More differentiated rocks tend to have more radiogenic Sr, but the values vary widely and show no clear relationship between the degree of differentiation and assimilation of radiogenic Sr.

Relations to Subduction

Remarkably little evidence has been found to relate the Cascade magmas to oceanic lithosphere or sediments. Nearly all workers who have so far examined the petrological relations, trace elements, or isotopic compositions of the rocks have concluded that they reflect a primary mantle origin with little if any contribution from subducted crustal rocks (e.g. Smith and Carmichael, 1968; Peterman *et al.*, 1970; Church and Tilton, 1973; Condie and Swenson, 1973; Church, 1976; White and McBirney, 1978).

No correlation has been found between the rates of production of igneous rocks in the Cascades and subduction along the adjacent plate boundary. The wide variation in the tempo of Cainozoic volcanism, not only in the Cascades but in the circum-Pacific as a whole, is in marked contrast to the nearly constant rates of sea-floor spreading deduced from the spacing of magnetic anomalies on the sea-floor (Kennett *et al.*, 1977). The same appears to be true of the intensity of recent volcanic activity, which varies widely from place to place with no detectable relationship to calculated subduction rates or the amount of crustal material that could be consumed in trenches (McBirney, 1971). The lack of such relations seems to argue against generation of calc-alkaline magmas by flux-melting when water is released by dehydration of subducted hydrous phases and rises into the overlying mantle. It has been pointed out (Fyfe and McBirney, 1975) that there must be a direct relation between the amount of water introduced into the mantle and that of phlogopite reaching depths of 100–150 km in the down-going slab. Because the stability of phlogopite is directly dependent on the amount of K in the rocks, there should be a good correlation between the amount of magma generated and the rate at which the system recycles K (as well as other components that have high solubilities at elevated temperatures and pressures).

One can compare the amount of K entering the oceans from the continents with that being returned to the continents in calc-alkaline magmas and demonstrate a crude balance, at least in orders of magnitude over a period of 20 Ma (McBirney, 1976), but any such calculation is no better than the assumptions on which it rests, and in this case it is little more than an attempt to fit inadequate data to an unproven hypothesis.

Conclusions

It is still too early to offer a comprehensive synthesis of the complex igneous history of the Cascade region, and it would be even more premature to propose that the causes of orogenic volcanism can be discerned in the dim record of events as they are now seen. At best, one can only note a few salient features that have emerged from recent studies.

Igneous activity has been strongly episodic with distinct pulses separated by periods in which there was little volcanism. Some of the episodes seem to have occurred in unison in widely separated parts of the circum-Pacific region. The volumes and compositions of rocks produced during successive periods have varied widely, but there appears to have been an overall decline in the magnitude of volcanism and a gradual change toward more basic compositions. Most petrological evidence points toward generation of magmas in the mantle wedge overlying the zone of subduction and contamination with lithophile components as the magma rises toward the surface.

Perhaps the most important conclusion that can be drawn from the evidence now available is that there is little direct relation, other than a spatial one, between volcanism in the Pacific North-west and the subduction that is commonly thought to be associated with it. Even the spatial relation is somewhat ambiguous because, as the Tertiary record shows, andesitic volcanism has seldom been concentrated in long linear belts near the continental margin as it is today. Even during Quaternary time, andesitic volcanoes are by no means confined to island arcs and continental margins; many are found well within the continental interior.

The ultimate cause of andesitic volcanism in the Cascade province is still unknown.

Acknowledgements

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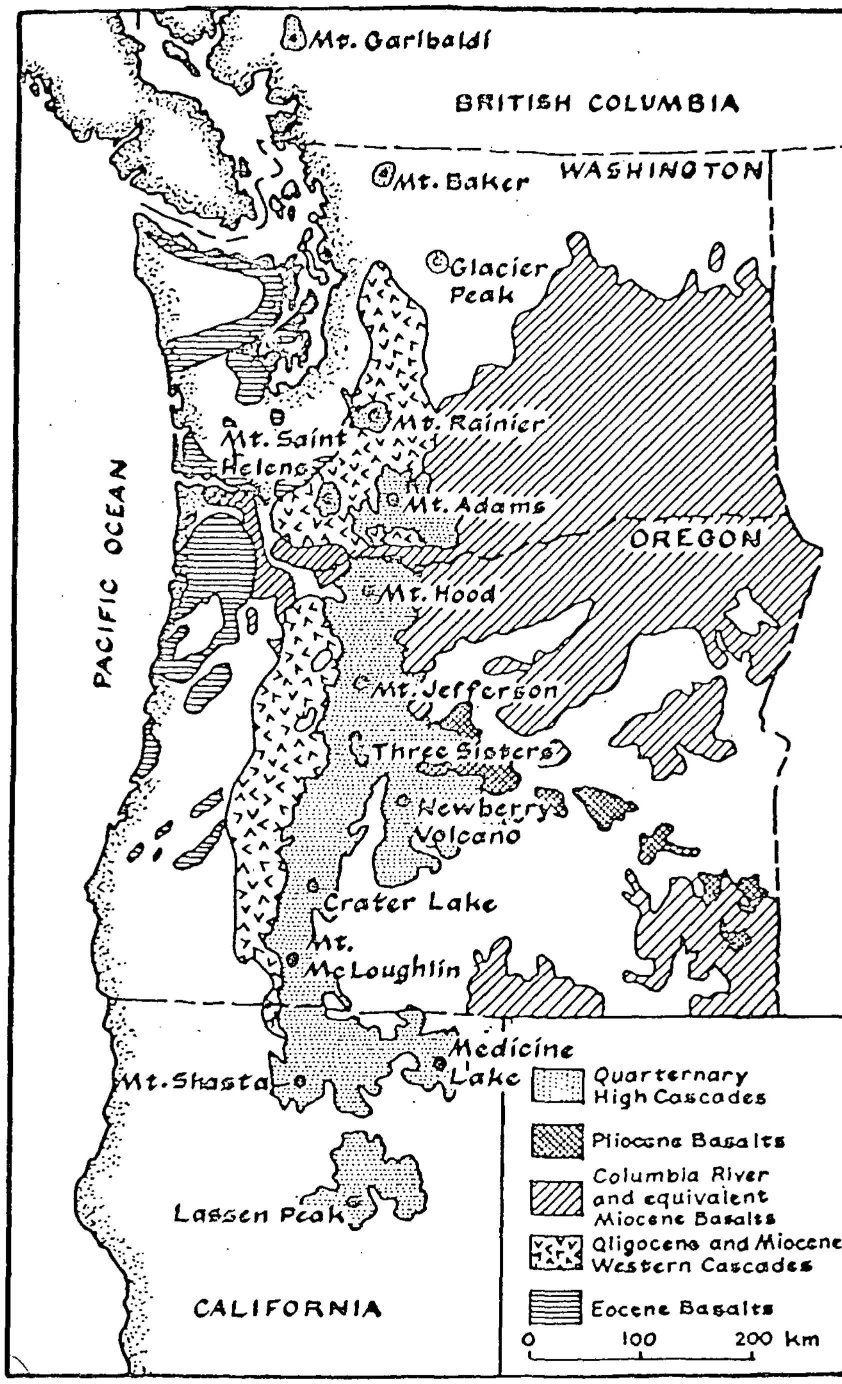

Fig. 1 Generalized map of the Cascade Range and adjacent parts of the north-western United States

North Santiam mining area, Western Cascades — relations between alteration and volcanic stratigraphy: Discussion and field trip guide

by J. Michael Pollock and Michael L. Cummings, Department of Geology, Portland State University, P.O. Box 751, Portland, Oregon 97207

Part I. Discussion*

INTRODUCTION

General

While it has been postulated for some time that porphyry copper mineralization develops beneath subduction-related stratovolcanos, little is known about the subvolcanic environment above the mineralized zones and about the ground surface at the time of mineralization. The nature of fluid movement within the volcanic pile, timing of porphyry mineralization relative to volcanic activity, timing of the development of alteration relative to porphyry and vein mineralization, and possible surface geothermal expressions of the system need evaluation. Uplift of the Western Cascade Range relative to the High Cascade Range, which began approximately 5-4 million years before the present (m.y. B.P.) (Priest and others, 1983), has resulted in a deeply dissected terrain in which more than a kilometer of the stratigraphy overlying the porphyry copper-related mineralization in the North Santiam mining area is preserved and exposed. Thus the mining area provides the necessary setting in which to study the subvolcanic portions of a porphyry copper system.

The North Santiam mining area is located near the headwaters of the Little North Santiam River (Figure 1). Metal mineralization and alteration are zoned and centered on intrusions with associated tourmaline-bearing breccia pipes (Figure 1). Disseminated copper mineralization typical of a porphyry copper deposit has been documented by Callaghan and Buddington (1938) and Olson (1978).

This paper and field trip guide are based on part of a Portland State University master's thesis on the geology and geochemistry of the eastern portion of the mining area (Pollock, 1985). The road log, which will appear in next month's issue, begins near Salem, Oregon, and proceeds to the edge of the mining area. The actual tour of the mining area is on foot and is 4.7 mi each way. An optional side trip by car over French Creek Ridge to Detroit is also included.

In addition to the maps in this guide, it is recommended that 15-minute topographic maps of the Mill City and Battle Ax quadrangles (available from the Oregon Department of Geology and Mineral Industries and many sporting goods stores) and the Willamette National Forest map (available from the Detroit Ranger Station, U.S. Forest Service [USFS]) be used on this trip.

Mining history

The North Santiam mining area is one of five mining districts located in the Western Cascades of Oregon. The geology of the districts and an overview of the mineralization contained therein were presented by Callaghan and Buddington (1938). Current and abandoned workings were described and production from base metal and gold veins was reported by the Oregon Department of Geology and Mineral Industries (1951) and Brooks and Ramp (1968). The history of the mining area has recently been compiled by the Willamette National Forest (Cox, 1985) and the Shiny Rock Mining Company (George, 1985).

Exploration for gold in the North Santiam mining area dates back to the 1860's. The Ruth Vein, which was discovered in the early part of this century near the eastern end of the mining district (Figure 1), has been the focus of mining efforts for zinc and lead periodically since its discovery. Callaghan and Buddington (1938) applied the name "North Santiam mining area" to all the mineral claims along the North Santiam River and its tributaries. However, the area has previously been known by many different names (George, 1985). Claims along the Little North Santiam and its tributaries to the east of Gold Creek are held by the Shiny Rock Mining Company. Jawbone Flats, which was constructed in 1932, originally consisted of more than 30 structures, approximately half of which still remain (Cox, 1985) and are actively used as the mill site and operational headquarters for the claim block. The current ore mill, which was constructed in 1976, utilizes equipment from the original Amalgamated Mill at Jawbone Flats and the Lotz-Larsen Mill, which stood near Gold Creek (Cox, 1985).

Recent exploration in the North Santiam mining area has focused on the potential for porphyry copper mineralization in the central portion of the mining area. Reconnaissance mapping, geological chip sampling, and drilling of two holes totaling 1,255 m were performed from 1976 to 1978 by Freeport Exploration Company under lease agreement with Shiny Rock Mining Company (Decker and Jones, 1977). Amoco Minerals Company, which optioned the Shiny Rock Mining Company claim block beginning in 1980, conducted additional field mapping, soil geochemistry, an induced polarization-resistivity survey, and additional drilling. Ten core holes totaling 1,518 m were drilled during 1981-1982 (Dodd and Schmidt, 1982). Amoco Minerals continues to hold a block of claims, primarily along Cedar Creek, west and south of the Shiny Rock Mining Company claims. Drilling has been conducted, especially at a breccia pipe along Cedar Creek.

GEOLOGIC SETTING

Stratigraphy

Stratigraphic relationships in the Western Cascades reflect the complicated nature of subaerial volcanism and have been further complicated by the stratigraphic names and interpretations proposed by various researchers. A correlation chart presented in Figure 2 shows the regional stratigraphy (Priest and others, 1983).

The strata along the Little North Santiam River are primarily those of the Sardine series of Thayer (1936), as extended by Peck and others (1964). The type locality of the Sardine series was defined at Sardine Mountain located northwest of Detroit. Peck and others (1964) reported the Sardine Formation between the Little North Santiam and the Sandy Rivers as comprising two units, the lower, 300 to 600 m

*Part II, field trip guide, will appear in the next issue (January 1986). References at the end of Part I are for both parts.

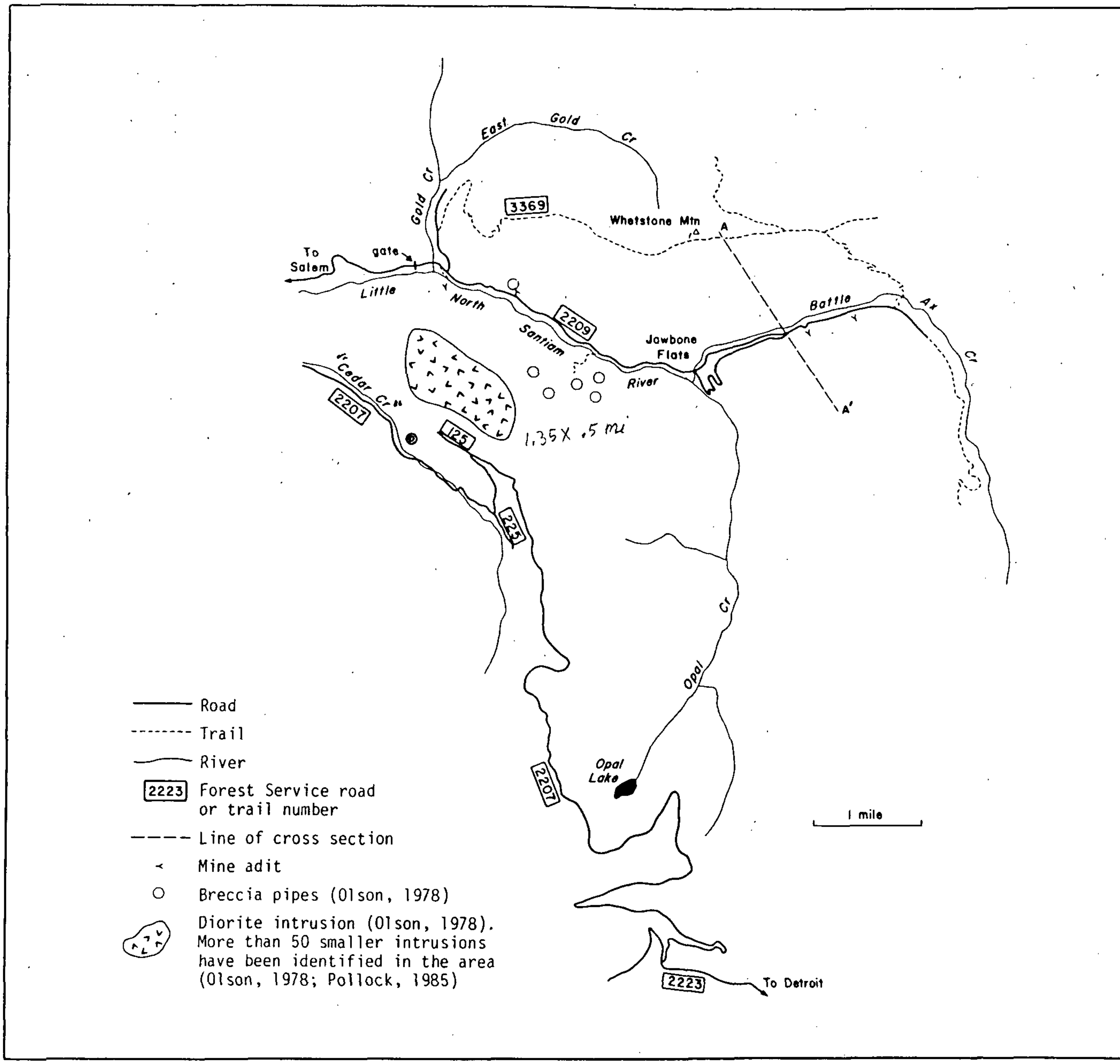

Figure 1. Map of the North Santiam mining area, located approximately 40 mi east of Salem in the Western Cascades. Map shows roads, streams, trails, major intrusions and breccia pipes, mine adits, and line for cross section A-A' in Figure 4.

lower
thick, of primarily fragmental andesites, and an upper unit, of approximately the same thickness, of hypersthene andesite flows. 300-600 m

White and McBirney (1979) separated the Elk Lake formation from the Sardine Formation on the basis of exposures in the Elk Lake area southeast of the mining area. They placed the Elk Lake formation as overlying and separated from the Sardine Formation by an angular unconformity.

Dyhrman (1976) named the pyroclastic rocks on Whetstone Mountain (Figure 1) the Whetstone Mountain volcaniclastic rocks. They are underlain in succession by the Thunder Mountain andesite, the Silver King andesite, and the Blister Creek tuff. The Blister Creek tuff was correlated by Dyhrman with the Little Butte Volcanic series of Thayer (1939); the other units were correlated with the Sardine series as mapped by Peck and others (1964).

Numerous plugs and dikes with compositions ranging from andesite or diorite to quartz monzonite and granodiorite apparently served as feeders for the middle and late Miocene volcanics of the Western Cascades (Thayer, 1939; Peck and others, 1964; White, 1980a). The center of volcanism for the Sardine Formation was interpreted by Peck and others (1964) to have been between the Middle Santiam River and the Collawash River.

Structure

Rocks of the Western Cascades are gently folded into a series of northeast-trending anticlines and synclines. The North Santiam mining area lies between the extensions of the Mehama anticline and the Sardine syncline, as defined by Thayer (1936). Callaghan and Buddington (1938) reported that dips north of the Little North Santiam River have a dominant northerly component, whereas those south of the river are dominantly southerly dipping, suggesting that the valley of the Little North Santiam River is near the crest of an anticline. White (1980b) estimated the age of northeast-trending fold structures to be between 15 and 11 m.y. on the basis of K-Ar dates for rocks of the Sardine Formation and the Elk Lake formation about 8 km southeast of the Ruth Mine.

Normal faults and intrusions with trends of N. 20° to 40° W. preceded and accompanied regional uplift of the Western Cascades relative to the High Cascades, which occurred 5 to 4 m.y. B.P. Northwest-trending lateral faulting spans a much longer time from 15 to 2 m.y. B.P. (Priest and others, 1983).

GEOLOGY OF THE NORTH SANTIAM MINING AREA

Stratigraphy

The stratigraphic units in the eastern portion of the mining area were assigned arbitrary letter designations by Pollock (1985) beginning with the lowest unit (Unit A) through the uppermost unit (Unit D). A generalized columnar section is shown in Figure 3.

Unit A: Unit A is comprised of moderately to extensively altered fragmental rocks of andesitic composition. The lapilli tuffs are generally medium to dark green in color; however, with increasing alteration, their clastic textures are obscured, and they are easily mistaken for porphyritic andesite flows. In zones of intense alteration, tuffs are "bleached" to a white color and primary textures are completely destroyed.

The lowest member of this stratigraphic unit is a distinctive polymictic breccia that is moderately to extensively altered and well indurated. It forms narrow, deep potholes or long, narrow chutes in the stream beds of the Little North Santiam River, Opal Creek, and Battle Ax Creek in secs. 28, 27, 33, and 29.

Overlying the polymictic breccia and forming the bulk of Unit A is a sequence of andesitic lapilli tuffs. Outcrop heights suggest that the thicknesses of individual cooling units range from 10 to 50 m. Lapilli-size lithic fragments are similar to the clasts in the polymictic breccia. Pumice is present in some units, and, from textures observed in thin section, glass is postulated as an original component of much of the groundmass. Flattened lapilli and pumice fragments in some tuffs suggest welding through parts of the units.

Unit B: Overlying and interlayed with the lapilli tuffs is a sequence of generally medium-gray, platy to block-fractured porphyritic andesite flows. Many fracture surfaces are a characteristic reddish brown. Phenocrysts of plagioclase and pyroxene are present in an aphanitic groundmass. Clinopyroxene dominates over orthopyroxene. Early-formed amphiboles are suggested by the shapes of masses of opaque minerals outlining relict phenocrysts.

Unit C: Unit C is a sequence of andesitic to dacitic or rhyodacitic tuffs and hornblende andesitic flows. The lower tuffs resemble the lithic tuffs of Unit A. On Whetstone Mountain, they contain distinctly smaller lithic clasts and a greater percentage of crystal fragments. Upper tuffs contain quartz and/or hornblende crystals and abundant pumice. A flow within Unit C contains hornblende phenocrysts and is exposed along the southern boundary of sec. 35.

Within Unit C on Whetstone Mountain at an elevation of 1,400 m is a distinctly laminated, fine-grained deposit that is between 20 and 25 m thick. Rocks in this deposit display parallel, 1- to 2-mm-thick laminations of alternating light- and dark-colored materials. Individual laminae may be traced for more than 10 m along the outcrop face. Where the rocks contain hydrothermally introduced carbonate, they form cliffs. Carbonized plant fragments, including twigs up to 5 cm in length, needles, and possible seed pods, are locally abundant. Although strong lineation in these fragments is commonly noted, the orientation among layers is not constant. Where the tuff is not strongly indurated, the resulting creep produces

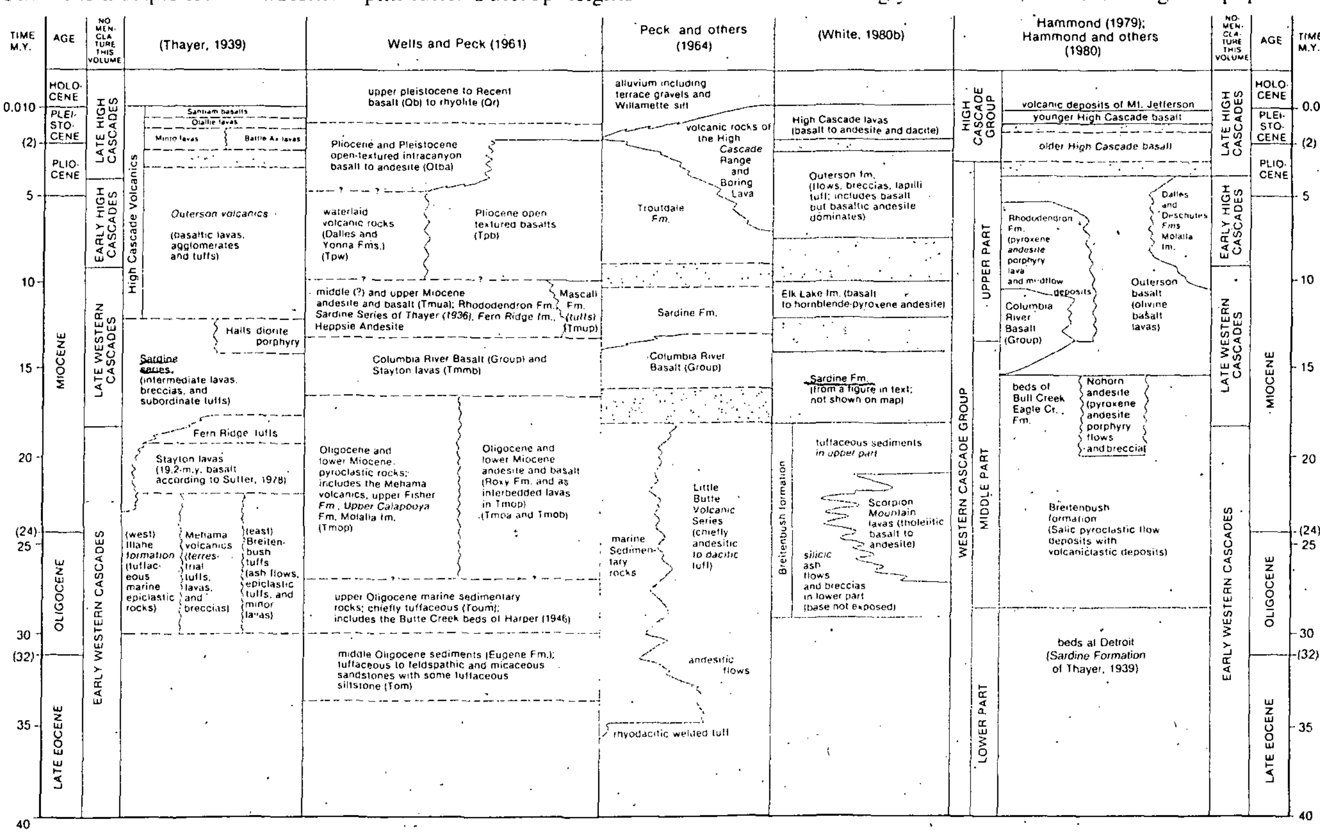

Figure 2. Correlation of regional stratigraphic units (from Priest and others, 1983).

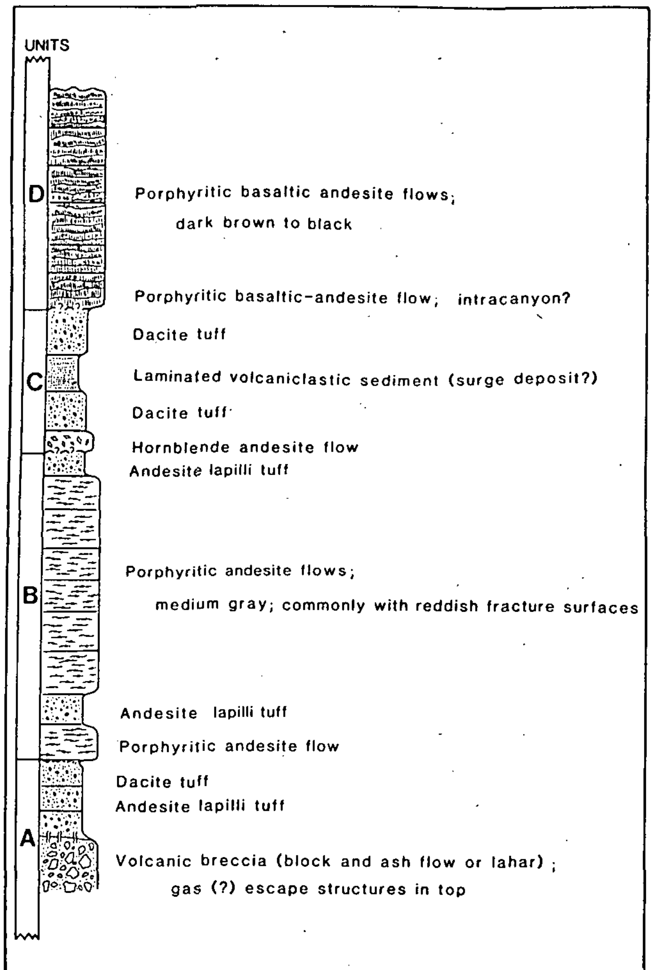

Figure 3. Generalized columnar section for the eastern portion of the North Santiam mining area (Pollock, 1985).

dramatically distorted tree growth in the old-growth timber. A distinct receding topographic bench and areas of significant creep at this stratigraphic position throughout the area south of Battle Ax Creek suggest that Unit C is present.

Unit D: Unit D consists of a sequence of dark-colored porphyritic basalts and basaltic andesite flows. Phenocrysts are plagioclase and pyroxene. Some flows are glomerophyric, and several have abundant lath-shaped pyroxene phenocrysts up to 2 mm in length. Orthopyroxene is the dominant pyroxene and is commonly partially to completely uralitized, whereas subordinate augite is fresh. Plagioclase anorthite contents range from 55 to 62 percent.

Capping Whetstone Mountain at an elevation of 1,480 m are two flows of Unit D, each 12-15 m thick. Flows of Unit D are found above an elevation of 1,040 m south of Battle Ax Creek. Lower flows in the sequence were deposited as intracanyon flows into the tuffs of Unit C.

Intrusions

Originally all intrusions in the mining area were reported as dioritic (Callaghan and Buddington, 1938). However, Olson (1978) divided the intrusions into seven units ranging in composition from basaltic andesite to quartz latite/rhyodacite. He interpreted the youngest unit to be a granodiorite typified by the large intrusion near the center of the mining area (sec. 32) and represented in the vicinity of the Ruth Mine by narrow, northwest-trending dikes. A K-Ar date for a hornblende separate from this large intrusion was reported as 13.4±0.9 m.y. (Power and others, 1981a).

In the eastern portion of the mining area, three major types of intrusions are distinguished (Pollock, 1985): an equigranular diorite, a porphyritic diorite, and a quartz-feldspar porphyry. Narrow aphanitic to porphyritic andesite dikes are also found at several locations, including Level 5 of the Ruth Mine, where they are associated with strong alteration halos but no base metal mineralization.

The equigranular diorite is best exposed along Battle Ax Creek, where it occurs as northwest-trending dikes. The equigranular texture of the feldspar and mafic phases produces a distinctive "salt and pepper" appearance. Vesicles are common, particularly near contacts. Contacts are sharp with narrow chilled margins. Locally, narrow, 0.5- to 3.0-cm-wide, white aplite veins cut these intrusions.

Porphyritic diorite intrusions also form northwest-trending dikes. The dikes commonly contain glomerocrysts of plagioclase and pyroxene. Dikes are best exposed adjacent to the portal of Level 5 of the Ruth Mine, in the adit, in a roadcut above the portal, and in Battle Ax Creek downstream from the portal. These intrusions are similar in mineralogy, texture, and chemistry to the large intrusion mapped by Olson (1978) in the central part of the mining area.

The third intrusion type is leucocratic quartz-feldspar porphyry. It is light gray to white in color and has 5 to 10 percent quartz phenocrysts that are 0.5 to 2 mm in diameter and euhedral to nearly round in shape. Plagioclase phenocrysts are also present, and potassium feldspar may have been present originally. Occasional hornblende crystals to 2 mm in length occur.

The geometry of the quartz-feldspar porphyry intrusions is very irregular. The contacts are steeply dipping to nearly horizontal at different outcrops and within the same outcrop. Below the portal of the Ruth Mine in Battle Ax Creek, a sill appears to intrude and dome the polymictic breccia of Unit A. Within the Ruth Mine, this intrusion is well exposed, and its margin serves as a host for mineralization. On Whetstone Mountain, the intrusion becomes increasingly jointed with increased elevation. At an elevation of 950 m, the highest exposures form a 30- to 35-m-high pinnacle that displays well-developed, steeply dipping columnar joints.

Structure

All units within the area are nearly horizontal to gently dipping to the southeast, as illustrated on the cross-section in Figure 4. Measured dips range from 5° to 20°. The dip of the contact between Units A and B is approximately 11°-13°. Dips decrease higher in the section and to the south. Units B and C thin to the north because of a decrease in the number of flows and tuffs and also as a result of a thinning of individual deposits. The base of Unit A is not exposed, and the top of Unit D has

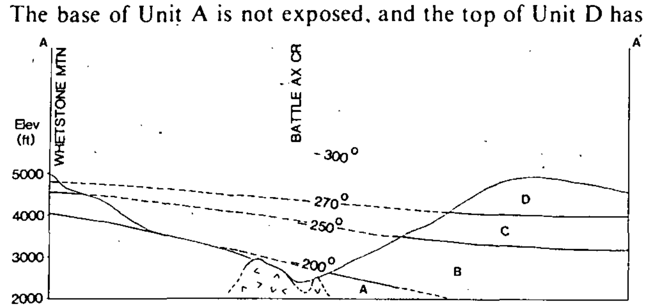

Figure 4. Geologic cross section of the Ruth Mine area, eastern portion of the North Santiam mining area. Cross-section line is shown in Figure 1. Geologic units are those shown in Figure 3. Minimum burial depths required to prevent boiling of geothermal solutions of the temperatures indicated are shown. Results of fluid-inclusion data (Table 1) suggest that the land surface at the time of mineralization was at or above the level of Units C and D (modified from Pollock, 1985).

been removed by erosion.

Three high-angle fracture and fault sets occur in the study area. The most prominent set is oriented N. 40° to 50° W. and controls the trends of several creeks and the emplacement of diorite dikes. The second is oriented N. 5° to 20° W. The third is oriented from N. 80° E. to east-west.

Displacements are difficult to determine because (1) exposure is poor; (2) lithologic units are similar in appearance; and (3) along Battle Ax Creek where exposures are the most extensive, faults have been the loci of dike emplacement. Slickensides are nearly horizontal. Where east-west faults and N. 45° to 50° W. faults intersect within the Ruth Mine, the east-west faults either offset or bend into alignment with the northwest faults with no apparent offset. The N. 5° to 20° W. fractures cross both sets without apparent displacement.

ALTERATION AND MINERALIZATION

Alteration types and distribution

Within the North Santiam mining area, Olson (1978) identified a zoned alteration system centered in the eastern half of sec. 19, T. 8 S., R. 5 E. The central potassium silicate zone contains an assemblage of biotite, quartz, sericite, kaolinite, and small quantities of potassium feldspar. Biotite, interpreted as replacing hornblende and augite, has been subjected to retrograde alteration to chlorite. Surrounding the potassic zone is phyllic alteration consisting of an assemblage of quartz, sericite, and kaolinite. Olson noted that the phyllic alteration is strongly controlled by structures, with the most extensive alteration along and adjacent to northwest-trending faults. Within this phyllic zone, tourmaline is found in breccias and is associated with quartz and sericite. Olson interpreted the geometry of these breccias to be "pipe-like." A whole-rock age in one of these breccias was reported as 11.0±0.4 m.y. (Power and others, 1981b). Outside of the phyllic zone, Olson reported pervasive propylitic alteration assemblages of chlorite, epidote, carbonate, and quartz extending well beyond the boundaries of the mining area and grading imperceptibly into unaltered rocks. The presence of breccia pipes and zoned alteration together with zoned mineralization from predominantly chalcopyrite/bornite outward to chalcopyrite/pyrite to base metals (Callaghan and Buddington, 1938; Olson, 1978) led Olson to propose a porphyry copper model for the area.

In the eastern portion of the mining area, alteration is most intense at lower elevations. Alteration decreases to the south and east (Pollock, 1985) and with increase in elevation.

Propylitic alteration consists of the replacement of (1) primary mafic minerals by one or more of the minerals chlorite, calcite, and epidote; and (2) plagioclase by albite and epidote or calcite. It is widespread but becomes more intense in the vicinity of northwest-trending structures and intrusions. In the least altered rocks, only amphiboles and uralitized pyroxenes are altered to chlorite. Rocks exhibiting this degree of alteration may contain calcite or chlorite-calcite veinlets.

At lower stratigraphic levels, epidote occurs as a replacement of mafic and plagioclase phenocrysts. Locally, epidote and quartz are precipitated in veinlets and as vesicle fillings. Veinlets and vesicles have halos extending up to 3 cm into their walls in which epidote replaces groundmass minerals. This is especially well illustrated by the alteration of the equigranular diorite dikes near the confluence of McCarver and Battle Ax Creeks.

Phyllic or quartz-sericite-pyrite alteration is characterized by the replacement of groundmass and phenocrysts by fine-grained micas and quartz. Phyllic alteration is recognized in the field by a loss of primary textures and bleached halos around veins, faults, and larger fractures. Bleaching destroys primary mafic phases and secondary phases such as chlorite. Iron removed from these phases is generally retained in the rock as disseminated pyrite.

Phyllic alteration is best developed in the tuffs near faults and within breccias in the quartz-feldspar porphyry intrusions.

Argillic alteration, characterized by moderate to total replacement of rocks by kaolinite, is best developed along N. 30°-40° W. and N. 80° E. faults. Argillic alteration is generally limited to hanging-wall breccia zones along faults. Clay zones range in thickness from a few centimeters up to 3-4 m at places in the Ruth Mine. Fragments of partially altered host rocks are found within the clay. X-ray analysis of clay zones confirms the presence of kaolinite as well as sericite and chlorite believed to be relict from previous alterations. Swelling clays are absent from all analyzed samples of vein clay.

Precipitated stilbite and laumontite have been identified as vein materials at lower elevations. The distribution of these zeolite veins has not been determined. Veins with fibrous laumontite near the vein walls and euhedral stilbite in the core cut an equigranular diorite dike along Battle Ax Creek.

Base metal veins

Quartz veins, with or without calcite, serve as hosts for sulfide mineralization in the eastern portion of the area. The following generalized paragenetic sequence occurred: Host rocks were propylitically altered and then brecciated. Growth of early quartz crystals in open space resulted in euhedral quartz attached to the breccia fragments and vein walls. Sulfide minerals seldom grew in contact with the vein walls but were precipitated with early quartz. Brecciation that followed quartz deposition apparently opened additional fracture surfaces in some veins. Coarse-grained calcite crystals completely or partially filled some of the open space.

A sample from a small vein located in Battle Ax Creek near the Morning Star Mine displays overgrowths of chalcedonic quartz. In this vein, sulfide deposition preceded the precipitation of the chalcedony and is in contact with it in several places. Many veins show a second stage of fine euhedral quartz crystals perpendicular to the faces of the first stage.

Base metal mineralization in the vicinity of the tourmaline-bearing breccia pipes consists of both disseminated and vein chalcopyrite. Veins display moderate to strong northwest orientations and strong phyllic alteration halos (Olson, 1978).

East of Jawbone Flats, the highest base metal concentrations are found in veins of the Beuche Group, the Ruth Mine, and the Morning Star Mine. Veins in these mineralized areas are localized along the N. 40° to 50° W. structural trend. They are most abundant and contain the highest quantities of ore minerals near contacts between intrusions and the tuffs of Unit A. In each of these three mineralized areas, sphalerite is the main ore mineral; galena and chalcopyrite occur in lower abundance. Pyrite is present in the veins but is also found in other veins in which base metal sulfides have not been detected. Chalcopyrite forms solitary grains and occurs as minute blebs commonly 0.05 mm in diameter within sphalerite grains. Within the Ruth Mine, sphalerite and galena are also deposited on fracture surfaces in an open-space "crackle" breccia developed in an intrusion of quartz-feldspar porphyry.

Fluid-inclusion data

Fluid-inclusion data on the composition and temperatures of crystal formation have been obtained for quartz from three veins displaying phyllic alteration in the eastern part of the mining area. Salinities are low, with a freezing-point depression range corresponding to 1 to 6 wt percent NaCl equivalent. No daughter salts or other solid phases have been identified within the fluid inclusions. The range of homogenization temperatures is shown in Table 1. Of these three veins, only the Beuche sample site contains significant sulfide mineralization other than pyrite.

In addition, fluid-inclusion data from quartz crystals

Table 1. *Fluid-inclusion data from quartz-calcite veins in the general area of the east end of the North Santiam mining area. All analyses were performed on quartz crystals.*

Location within study area	Vein name	Number of inclusions analyzed	Freezing range	Homogenization range	(median)	Comments
East	Morning Star(?)	10	-0.6° to -1.8°	216° to 245°	(220.5°)	Core of crystal on vein wall
		6	-1.4° to -2.1°	204° to 234°	(218.0°)	Inclusion-rich rim of same crystal
Central	Unnamed vein of Beuche claims	3	-0.6° to -1.0°	227° to 236°	(230.4°)	Core of crystal near center of vein; Inclusions very rare
		5	-0.6° to -1.7°	282° to 299°	(287.8°)	Crystals adjacent sphalerite/galena mineralized band
West	Unnamed prospect	5	-0.9° to -3.8°	225° to 256°	(247.1°)	Core of crystal near vein wall

collected from quartz-epidote veins cutting an equigranular diorite dike along Battle Ax Creek show homogenization temperatures ranging from 245° to 310° C. Salinities of these inclusions are below 2 wt percent NaCl equivalent. Base metal sulfide mineralization is absent in these veins, and pyrite is sparse.

DISCUSSION

The subvolcanic environment of a porphyry copper system can be inferred from the North Santiam mining area on the basis of stratigraphic relationships, absolute and relative age relations, intrusive history and its relation to volcanism and mineralization, and the chemistry of hydrothermal solutions responsible for alteration and mineralization during the history of the system. The following points are pertinent to construction of a model for the system.

1. The subvolcanic portions of a porphyry copper system are geothermal systems in which alteration patterns, mineralization, and boiling zones are related to depth beneath the ground surface at the time the system is active. Determination of the nature and position of the ground surface at the time of alteration and mineralization allows determination of those processes that occur at shallow depths within a developing porphyry system.

2. The homogenization temperatures of fluid inclusions from the North Santiam mining area indicate that the depth of formation of veins in the eastern part of the district was at least 800 m at the time of mineralization. The fluid inclusions do not indicate boiling of the ore solutions. The 800-m depth is the minimum depth required to prevent boiling of solutions of the temperature and salinity of those found in the study area. This depth of formation would place the ground surface at the time of mineralization near the level of unit C (see Figure 4).

3. In an unmapped area aong the west end of French Creek Ridge is a bedded pyroclastic deposit of probable rhyodacitic composition (Cummings and Pollock, 1984). Individual beds are from 5 to 10 cm thick and are distinguished by alternating light and dark layers. Based on elevation and apparent stratigraphic position, this unit is believed to be a member of the lower Elk Lake formation of White (1980b). Pollock (1985) argued that this unit is a surge deposit, the distal facies of which is the finely laminated deposit of Unit C on Whetstone Mountain 6.5 km to the north. Based on this correlation and the description of flows given by White (1980b), the flows of Unit D correlate with the upper Elk Lake formation. Dates reported by White (1980b) for rocks mapped as Elk Lake formation on French Creek Ridge range from 11.8 to 11.0 m.y. B.P.

4. Pollock (1985) postulated the order of intrusions in the eastern portion of the mining area to be (1) equigranular diorite, (2) porphyritic diorite, and (3) quartz-feldspar porphyry. Porphyritic diorite dikes penetrate strata correlative with Unit B (Olson, 1978); but no locations are known where intrusions are in intrusive contact with rocks of either Unit C or D. Based on geometry and similiarity in composition, the quartz-feldspar porphyry intrusion may have been a feeder for one of the tuffs of Unit C. These relations suggest that the exposed diorite intrusions probably were not the heat sources that drove the hydrothermal system in the area. The quartz-feldspar porphyry may have been the heat source, but this relation is not certain.

5. Mineralization is found in or along the margins of the major intrusion types including within "crackle" breccias developed in the quartz-feldspar porphyry. Thus mineralization, at least in part, postdates emplacement of the youngest intrusions. The porphyritic diorite intrusions are believed to be genetically related to the intrusion in the central portion of the mining area that was dated at 13.4 m.y. B.P. (Power and others, 1981a). Sericitic alteration associated with porphyry mineralization in the district has been dated at 11.0 m.y. B.P. (Power and others, 1981b). The quartz-feldspar porphyry intrusion has not been dated.

6. Mineral assemblages typical of propylitic alteration occur under two extremes of hydrothermal conditions. At low water-to-rock ratios, pervasive isochemical recrystallization to epidote-chlorite-calcite is analogous to greenschist facies metamorphism. This may occur as a result of burial depth and elevated thermal gradients resulting from emplacement of intrusions. At high water-to-rock ratios, propylitic alteration assemblages (Giggenbach, 1984) develop in downflow zones of geothermal systems. In contrast, phyllic and potassic alteration assemblages form in upflow zones (Giggenbach, 1984).

7. The alteration history of the study area is one of regional propylitic alteration developed at low water-to-rock ratios. Later, development of zones of fluid upflow occurred along the margins of dikes and along faults. The base metal sulfide mineralization occurred in quartz veins within sericitic envelopes of fluid upflow zones as ascending solutions cooled.

Argillic alteration developed later under conditions of an acidic system. Propylitic alteration associated with quartz-epidote veins may represent fluid recharge channels contemporaneous with mineralization. Fluids responsible for this alteration also utilized the vertical permeability of intrusion margins.

SUMMARY AND CONCLUSIONS

Base metal mineralization and alteration in the eastern portion of the North Santiam mining area developed in response to hydrothermal fluids circulating through faults and along fractured boundaries of intrusions. The ground surface at the time of mineralization was the developing volcanic structure from which tuffs of Unit C and flows of Unit D were erupted. This developing center was the source of heat that drove the hydrothermal circulation system and may be the center responsible for the porphyry-style mineralization in the district.

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NEXT MONTH: FIELD TRIP GUIDE

Survey of Oregon offshore mapping released

The Oregon Department of Geology and Mineral Industries (DOGAMI) has released a survey of the needs of State agencies for offshore maps and the current status of available mapping products and programs that fill those needs.

A Survey of Oregon Offshore Mapping was compiled by Glenn W. Ireland, State Resident Cartographer, and has been published as DOGAMI Open-File Report 0-85-3. The 30-page report surveys, in its first part, all State agencies that coordinate their mapping through the State Map Advisory Committee and describes their programs and projects that require offshore maps. In its second part, the report identifies Federal agencies and independent sources that have produced offshore maps or are conducting offshore mapping programs. In both parts of the report, contact persons and addresses are provided for each agency.

The survey extends to the entire marine environment, including a variety of zones such as estuary, beach zone, shore, tidelands, near-shore zone, continental shelf, continental slope, and various ridges, rises, and fracture zones. It is intended to allow a variety of users to focus on offshore mapping needs for specific projects. It will also allow mapping planners to coordinate projects between different programs.

The new report, Open-File Report 0-85-3, is now available at the Oregon Department of Geology and Mineral Industries, 910 State Office Building, 1400 SW Fifth Avenue, Portland, OR 97201. The purchase price is $4. Orders under $50 require prepayment. □

North Santiam mining area, Western Cascades — relations between alteration and volcanic stratigraphy: Discussion and field trip guide

by J. Michael Pollock and Michael L. Cummings, Department of Geology, Portland State University, P.O. Box 751, Portland, Oregon 97207

Part II. Field trip guide*

ROAD AND TRAIL LOG

The route of the trip is shown in Figure 1. Mileage is indicated in this log by italicized numbers. The first set of numbers is cumulative throughout the field trip; the numbers in parentheses indicate the mileage between points. The portion of the trip that goes through the Shiny Rock Mining Company claims is to be traveled on foot and is 4.7 mi each way. For your safety, avoid open mine adits. Most are not maintained and are unstable and very dangerous.

0.0 mi (0.0 mi) Proceed east on Oregon Highway 22 from its intersection with Interstate I-5 (exit 253) on the southeast edge of Salem. The highway climbs out of the Willamette Valley into the Waldo Hills. These hills, the Salem Hills to the southwest, and the Eola Hills west of Salem are underlain by flows of the Columbia River Basalt Group (CRBG).

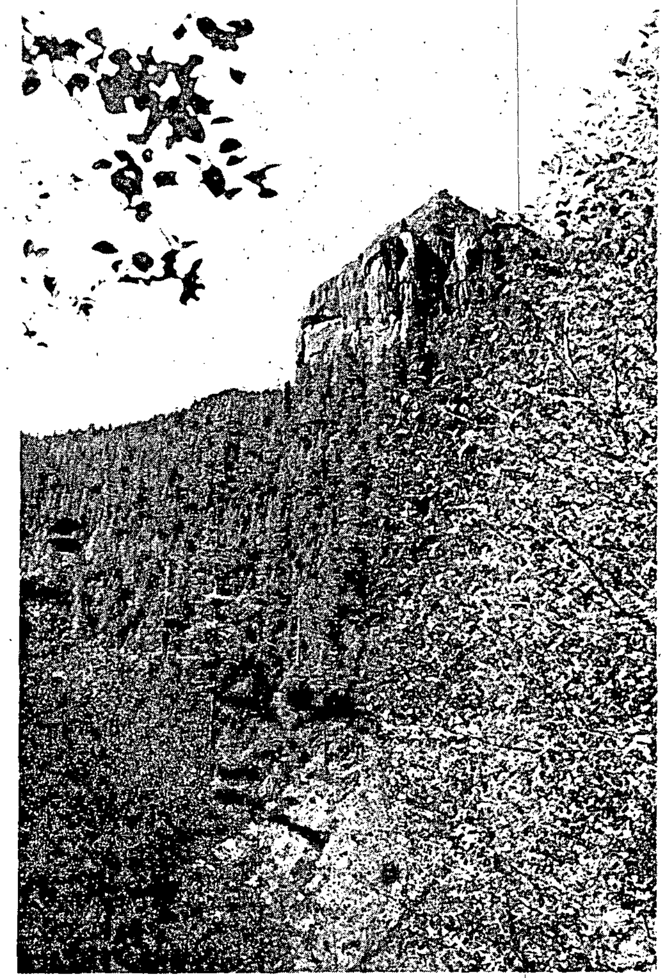
Thayer (1939) originally named these basalts the Stayton lavas, indicated that the rocks were similar to the CRBG, and tentatively correlated them with the CRBG. M. Beeson (oral communication, 1984) confirmed that the Stayton lavas are actually flows of the CRBG.

Tolan and others (1984), in their studies of the Neogene history of the Columbia River, indicated that the oldest identified channel of the Columbia River passed near Stayton, through the Salem Hills, and possibly west to the Pacific Ocean. This channel developed during "Vantage time," a period of time lasting for several hundred thousand years or longer between the last eruptions of CRBG flows of the Grande Ronde Basalt (15.5 m.y. ago) and the first eruptions of the Frenchman Springs Member of the Wanapum Basalt. The first flow of the Frenchman Springs Member to reach this area, the Ginkgo flow, followed this ancestral channel. Hoffman (1981) reported the thickness of the Ginkgo flow in the southeastern Salem Hills as 180 m.

As the road climbs the hills, note the red-colored laterite soils developed on these basalts. In the Salem Hills, ferruginous bauxite deposits have developed from the Frenchman Springs Member (Hoffman, 1981). These bauxite deposits are iron-rich and, in the Salem Hills, contain 13.4 million dry long tons of ore at 36.02 percent Al_2O_3; 4.17 percent SiO_2; and 32.49 percent Fe_2O_3 (Hook, 1976).

4.0 mi (4.0 mi) View to the east from the crest of the Waldo Hills toward the Cascade Range. The snow-covered peak in the distance is Mount Jefferson, one of the composite volcanos of the late High Cascade group of Priest and others (1984). Most of the hills in the intermediate distance are composed of rocks of the Western Cascade group of Priest and others (1984).

12.3 mi (8.3 mi) Sediments exposed in small outcrops are of the Illahe formation as defined by Thayer (1939). These sediments, which underlie the CRBG, are well-bedded, tuffaceous marine sandstones that were deposited in a marine



Mile 41.5. One of a pair of "stacks" between which Stack Creek flows and from which it derives its name.

embayment that occupied the Willamette Valley until the early Miocene (Baldwin, 1981). Orr (1984) studied the informally named "Butte Creek beds" northeast of this locality and assigned them to the Oligocene. Coal and limestone deposits occur within these beds. The sediments were deformed to dips ranging from 10° to 12° prior to eruption of the CRBG, which dips more gently (less than 3°).

Examination of this outcrop reveals distinct reverse grading (finer particles near the base and increasing in size toward the tops of individual beds) resulting from the tendency of pumice to float. Also present are abundant carbonized and uncarbonized plant materials.

14.5 mi (2.2 mi) Flows of the CRBG are exposed to the right and left of the highway as the road descends a small hill north of the town of Stayton. The road to the right enters Stayton, and in a quarry along the road, andesitic volcanic rocks that may be the

*Part I, discussion, and references for both parts appeared in last month's issue (December 1985).

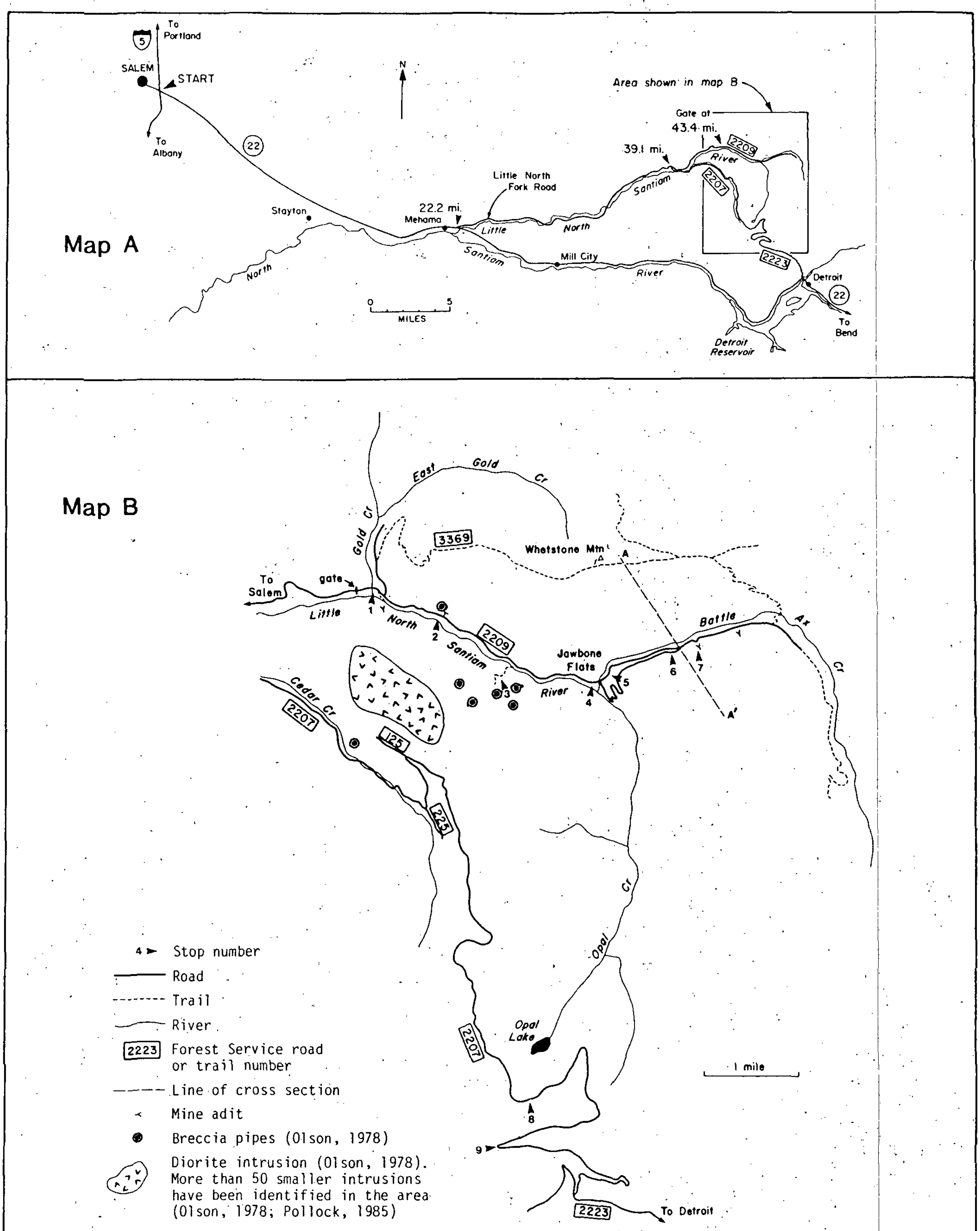


Figure 1. Map A. Route of field trip to North Santiam mining area, Oregon. Map B. Locations of key geologic features and field trip stops.

Mehama volcanics of Thayer (1936, 1939) are exposed.

21.4 mi (6.9 mi) Mehama-Lyons junction. *Continue on Highway 22 for 0.8 mi.*

22.2 mi (0.8 mi) Intersection with Little North Fork Road to the Little North Santiam Recreation Area along the Little North Santiam River. *Turn left (northeast).* The Little North Santiam River joins the North Santiam River immediately south of this intersection. Upper slopes of hills in this area are flows of the CRBG.

25.2 mi (3.0 mi) Exposures of a basalt intracanyon flow are located to the left on the north side of the road. The source of the basalt is not known. It is not basalt of the CRBG (M. Beeson, oral communication, 1984) but may be a flow from a High Cascade basalt shield volcano. The intracanyon flow can be observed at several localities along the road up the valley, suggesting that the ancestral Little North Santiam River was located in approximately its present location at the time the flow was erupted.

27.2 mi (2.0 mi) The irregularity in the road surface is due to active landslides. Deeply weathered volcaniclastic sediments in the cliff are involved in a particularly troublesome landslide. In the woods north of the road is the basalt intracanyon flow. Steep contacts between diverse volcanic units are commonly associated with slope failures.

28.3 mi (1.1 mi) BEWARE — the road takes a very tricky turn onto the bridge over the Little North Santiam River.

29.0 mi (0.7 mi) The basalt intracanyon flow is exposed in the quarry along the south side of the road. The jointing pattern is typical of the jointing developed in intracanyon flows.

33.6 mi (4.6 mi) Bridge over the Little North Santiam River. Rocks of the Mehama volcanics (Thayer, 1936, 1939) crop out along the river valley.

36.3 mi (2.7 mi) Entrance to Salmon Falls State Park.

37.3 mi (1.0 mi) Intersection with Evans Mountain Road. *Continue straight ahead on USFS Road 2209.* Evans Mountain is named for a mysterious prospector known as "Old Man Evans" who was found tortured and murdered on his claims. Local legend has it that Evans was finding sufficient gold to support an elegant life style. As in all such mining legends, the location of his "mother lode" has not been found. This legend and others of the area are recounted by Roberts (date unknown) in her book, *Elkhorn and Mehama: True Stories of Oregonians of the North Santiam*, which is usually available in the general store in Mehama.

38.4 mi (1.1 mi) Bridge over Henline Creek. North of USFS Road 2209 are abandoned workings on the Capital claim. The claim was patented as early as 1893. Most of the workings were caved by the 1930's. Veins have an average strike of N. 50° W. and dip of 75° to 80° SW. The veins are composed of a breccia of silicified andesite containing sericite and mesitite, an iron-magnesium carbonate. The breccia is cemented with stringers and veinlets of quartz with sulfides, chiefly sphalerite. There is minor galena and chalcopyrite (Callaghan and Buddington, 1938).

The Crown Mine, located to the south on the north flank of Elkhorn Mountain, was developed around 1927. Several veins were crossed in altered andesite, tuff, and volcanic breccia. A rhyolite is encountered near the contact of an intusive quartz diorite at the south end of the main crosscut. The Blind, Salem, Thirteen-Foot, and Winze Veins are along brecciated zones in which minor chalcopyrite, pyrite, and minor sphalerite are located within wall rocks mapped as tourmaline hornfels. These weakly mineralized veins strike from N. 55° W. to N. 60° W. (Callaghan and Buddington, 1938).

39.1 mi (0.7 mi) Intersection of USFS Roads 2207 and 2209. *Stay on USFS Road 2209 straight ahead at this intersection.* The road continues to follow the glaciated valley of the Little North Santiam River.

39.5 mi (0.4 mi) The area between this outcrop and the Ruth Mine was mapped by Olson (1978), who concentrated on the mineralization and alteration associated with breccia pipes in the area. Olson informally divided these rocks into upper and lower members of the Sardine Formation, and the lower member crops out along the road. The rocks in the major road cuts are andesite tuffs and contain accretionary lapilli, abundant lithic fragments, possible pumice fragments, and crystal clasts.

Epidote-lined fractures are present in the outcrop, and the common occurence of epidote in the tuffs is indicated by their yellow-green color.

39.7 mi (0.2 mi) The lithic-crystal tuff exposed in these road cuts contains accretionary lapilli.

41.5 mi (1.8 mi) Road crosses Stack Creek. To the north is a scenic view of the twin stacks on Henline Mountain.

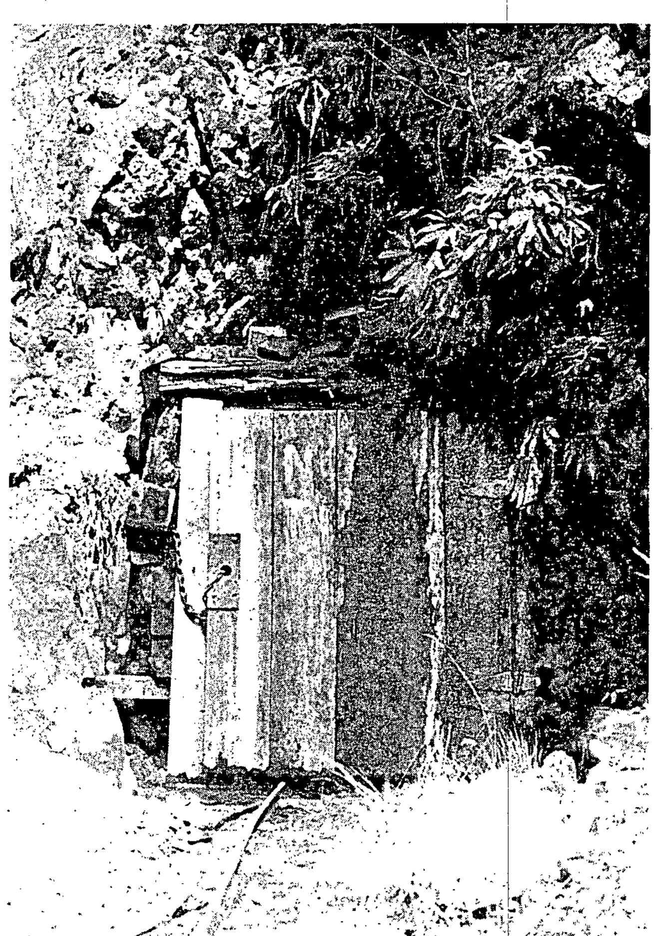
42.8 mi (1.3 mi) The road is very narrow and on the edge of a steep cliff into Horn Creek.

42.9 mi (0.1 mi) Road crosses Horn Creek after passing through a large pile of unconsolidated debris of glacial origin. The Black Eagle Mine is located at this point.

43.4 mi (0.5 mi) Gate at the west edge of the claim block controlled by the Shiny Rock Mining Company. *At this point park your car and proceed on foot. The Shiny Rock Mining Company is attempting to preserve the historic mining artifacts of the district, and your cooperation is appreciated. For your safety, avoid open mine adits, many of which are not maintained and are unstable.*

43.8 mi (0.4 mi) Bridge over Gold Creek.

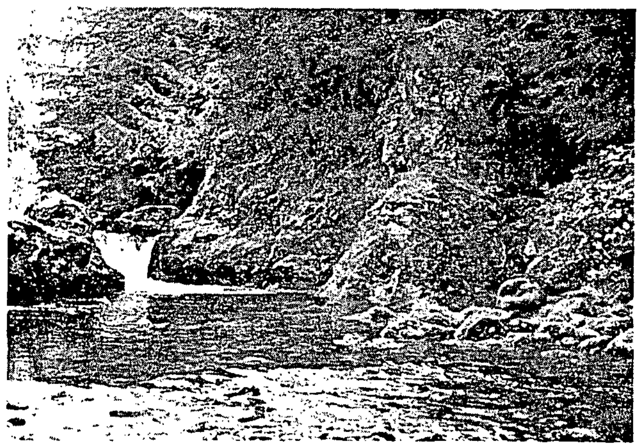
43.9 mi (0.1 mi) **Stop 1.** A short side road leads to the adit of the Santiam I Mine on the Little North Santiam River. This



Stop 1. The adit of Santiam I Mine is one of hundreds of mine adits and prospects in the North Santiam mining area.

mine has also been known as the Minnie E. and the Lotz-Larsen at various times in its history. Most of the development work was done in 1915-1917, with some ore shipped in 1924. The vein strikes N. 43° W. and dips 50° to 80° NE. and has been mined on both sides of the river. Ore minerals are distributed along the vein, but there are four distinct narrow ore shoots. Chalcopyrite is the principal ore mineral; pyrite and sphalerite are subordinate. Ore grades ranged from 1.25 to 4.47 percent copper and 0.1 to 1.22 oz of gold per ton. Locally the vein was up to 35 cm wide and composed primarily of chalcopyrite (Callaghan and Buddington, 1938).

The waterfall developed where the altered rocks of the vein were less resistant than the surrounding rocks. When the water level is low, the vein can be seen on the downstream end of the plunge pool. Waterfalls are common throughout the district and serve as one means of locating veins.



Stop 1. The Minnie E. Vein on which the Santiam 1 Mine adit is located crosses the Little North Santiam River and has been mined on both sides. Waterfalls such as the one in this photo commonly form where streams are able to downcut easily into the altered rock of the veins.

44.0 mi (0.1 mi) Whetstone Mountain trailhead. The trail, which is not included as part of this log, proceeds north along Gold Creek and then east along the ridge to the top of Whetstone Mountain. This well-maintained trail makes a scenic side trip, but it is over 5 mi to the top and moderately steep, with no water. The top of Whetstone Mountain can also be reached from the Clackamas River drainage. Maps are available from the Ripplebrook Ranger Station.

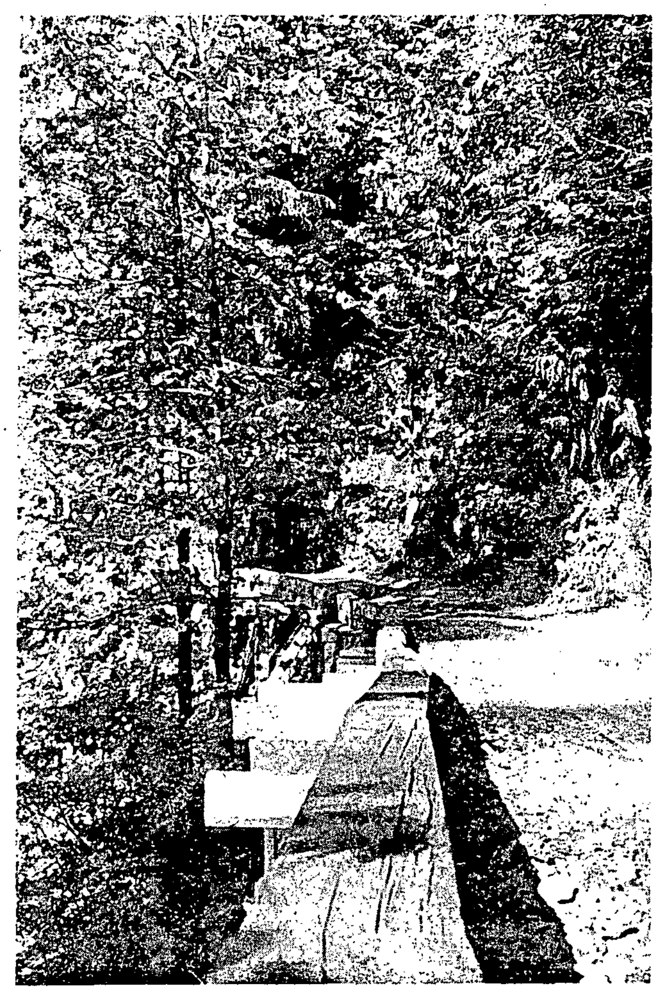
44.3 mi (0.3 mi) **Stop 2.** Half bridge along the north bank of the Little North Santiam River. An intrusion of porphyritic diorite forms a prominent cliff. Phenocrysts up to 8 mm long of blocky- to prismatic-shaped plagioclase comprises 15 percent of the rock. The dike has vesicles that have been filled by quartz. Plagioclase is altered to epidote, and hornblende is replaced by chlorite. The dike intrudes a lithic-crystal tuff, and xenoliths are common along its margins.

44.4 mi (0.1 mi) The Golden Bear mine workings are in a vein of the Santiam group of claims. This adit is located in what Olson (1978) mapped as a tourmaline-bearing breccia pipe. The rocks are brecciated, silicified, and sericitized. An adit has been driven into the alteration for nearly 270 ft along a bearing of N. 35° W. (Oregon Department of Geology and Mineral Industries, 1951).

44.7 mi (0.3 mi) This porphyritic diorite intrusion was mapped by Olson (1978) as an intrusion genetically related to the large intrusion located in the center of the mining area and dated at 13.4 m.y. B.P. (Power and others, 1981a). This intrusion follows a N. 30° W. trend along its eastern margin but is strongly sheared on a N. 10° W. trend on its western margin. This same relationship occurs for the porphyritic diorite dike near the Level 5 portal of the Ruth Mine.

45.4 mi (0.7 mi) The collapsed buildings to the south of the road are part of the Merten sawmill built in 1943. Two steam-driven capstans believed to have been salvaged from the battleship *Oregon* were used in this mill and remain on the site (Cox, 1985). One of the storage sheds is still standing near the east end of the mill site.

45.6 mi (0.2 mi) **Stop 3.** *Take the side road that crosses the Little North Santiam River on an old bridge to the south of the main road.* This road leads to the site of holes drilled by Amoco Minerals under lease agreement with Shiny Rock Mining Company. These holes are located in a cluster of tourmaline breccia pipes mapped by Olson (1978). The pipes, which are intensely altered and circular to elliptical in plan, range from 10 to over 100 m in length. Olson (1978) defined two types of breccia pipes: (1) shatter breccias of highly fractured rocks partially or completely altered to an assemblage of tourmaline, quartz, and sericite; and (2) "characterized by highly-altered angular to subrounded clasts cemented by quartz, sericite, tourmaline, oxides, sulfides, and rarely carbonate." In the first type of breccia pipe, there was little or no movement of fragments; in the second, the clasts have been displaced within the breccia. Zones of hydrothermal alteration extend 50 to 100



Stop 2. Half bridge, so called because the road is supported on one side by timbers and the other by the side of the valley, was required where the highly resistant rock of a large intrusion was encountered by the early miners in the North Santiam mining area.

m beyond the margins of the pipes. The last event in formation of the pipes was the filling of open-space veins with quartz.

Tourmaline occurs at this location as black rosettes, some of which surround chalcopyrite and are associated with secondary malachite. The best samples are found along the road and in small stream bed to the east. *Return to the main road.*

45.7 mi (0.1 mi) Lure No. 3 adit is developed beneath the level of the road. The rocks are brecciated and silicified. Rosettes of tourmaline occur in the silicified materials, and pyrite and chalcopyrite occur in the alteration zone.

46.6 mi (0.9 mi) **Stop 4.** Jawbone Flats, Oregon. This historic mining camp was built in the early 1930's and still serves as the operational headquarters for the mining activities in the district. *Please stay out of the buildings and away from equipment, and respect the historic artifacts that are present. On the east end of Jawbone Flats, a bridge crosses Battle Ax Creek about 0.25 mi north of where it joins Opal Creek to form the Little North Santiam River. Just across the bridge, a side road leads a short distance to the ore mill currently used by Shiny Rock Mining Company for processing ore from the Ruth Mine. Return to the main road.*

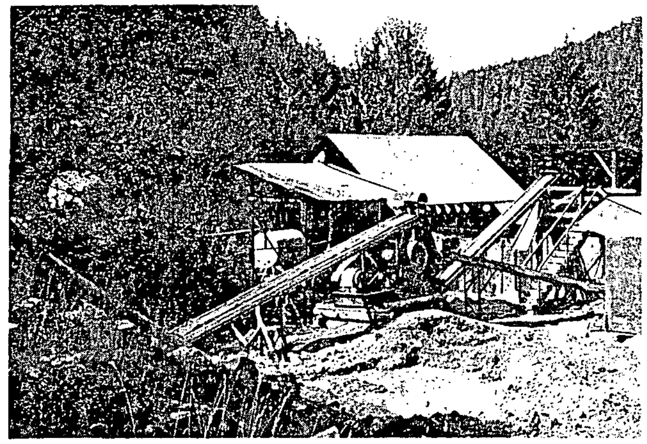
Stop 4. Jawbone Flats was constructed in 1932 as a mining camp and still serves as the operational headquarters for mining activity in the eastern portion of the North Santiam mining area. Of the 30 or so original buildings, about half are still in use.

46.8 mi (0.2 mi) **Stop 5.** At this site are the ruins of the original ore mill constructed by the Amalgamated Mining Company in 1932. This mill collapsed under heavy snows in 1949 (George, 1985). The original steam generator and other equipment are still visible. On the right side of the road was the old ore stockpile, and samples of ore from several of the veins in this part of the district can be found in this pile.

47.1 mi (0.3 mi) An unmarked trail leads to the left. This was an old tram road used to haul ore from the Ruth Mine to the mill. *Stay on the main road.*

47.5 mi (0.4 mi) A side road joins the main road at a sharp angle. In the stream bed of Battle Ax Creek below this point are several veins and adits of the Bueche Group of claims. The ruins of an old building are located on the north side of the road. *Stay on the main road.*

47.9 mi (0.4 mi) **Stop 6.** The road crosses a small tributary of Battle Ax Creek. Exposed in the road cut to the west of the creek is an outcrop of a quartz-feldspar porphyry intrusion. The rocks are nearly white in color, with an abundance of quartz and feldspar phenocrysts. To the east of the creek, an intrusion of equigranular diorite intrudes a tuff of Unit A. The creek is located on a fault, and alteration along this fault is visible in both intrusions. At the level of the tram road visible below, float from a collapsed adit suggests that this vein contains more



Stop 4. This operating ore mill located just south of Jawbone flats was constructed in part from equipment salvaged from earlier mills in the mining area.

chalcopyrite than is common in veins this far east in the district.

48.0 mi (0.1 mi) Road intersection. The road to the right leads to the adit of Level 4 of the Ruth Mine. *Stay to the left.*

48.1 mi (0.1 mi) Road intersection. **Stop 7.** The road that turns sharply to the left leads down to Level 5 of the Ruth Mine while the main road continues a short distance to a small creek. *Follow main road to small creek.* This creek, which is commonly called Ruth Creek, is downcut on the Ruth Vein. Adits have been driven on five levels of this vein. The open adit visible above the road is the fourth level and is collapsed where it encounters the vein. It was a primary producer of ore in the 1930's. Ore was removed by ore cart and dumped into a loading chute that is now collapsed at the road level. Ore samples from this adit can be collected in the stream.

Return to the road intersection. Take the steep lower road down to Level 5 of the Ruth Mine. A small roadcut along this road is located in a porphyritic diorite intrusion that is strongly sheared on its west margin. *When you reach the level of the tram road, STOP.* To the right is Level 5 of the Ruth Mine. This adit is being actively mined at present. *BEWARE of mining activities, and stay out.* Below the adit in the creek bed, an intrusion of quartz-feldspar porphyry cuts a coarse block breccia of Unit A. Just downstream, a dike of porphyritic diorite is visible as a resistant unit.

This concludes the trail log. Return to the main road and to your car by the same route. You may then return to Salem by the same route or take the optional route over French Creek Ridge.

OPTIONAL TRIP BEGINS AT INTERSECTION OF USFS ROADS 2207 AND 2209

At road log mile 39.1, take USFS Road 2207 to the southeast. Note: USFS Road 2207 is a logging road and not regularly maintained. It may be impassable in bad weather.

3.3 mi (3.3 mi) Bridge over the Little North Santiam River. On private land north of the road, Amoco Minerals Company has discovered a mineralized breccia pipe. The pipe is exposed in small outcrops on the north bank of Cedar Creek. Although discovery and drilling on the prospect were underway in 1981, no public announcement has been made, and no published information on the pipe is available.

5.1 mi (1.8 mi) Road crosses Cedar Creek.

5.5 mi (0.4 mi) Intersection of USFS Roads 225 and 2207. *Remain on USFS Road 2207 to the left.*

6.0 mi (0.5 mi) Intersection of USFS Roads 125 and 2207. *Stay on USFS Road 2207 to the right.*

9.2 mi (3.2 mi) Epidote-lined fractures are seen to cut rocks of the Sardine Formation in the roadcuts. The North Santiam mining area is approximately 3 mi to the north. Signs of hydrothermal alteration are common in the area, and epidote-lined fractures and propylitic alteration are typically noted.

10.2 mi (1.0 mi) A large dike crops out near where the road swings to follow the cirque wall to the east.

10.4 mi (0.2 mi) **Stop 8.** Overlook of Opal Lake, the headwaters for Opal Creek, which joins Battle Ax Creek at Jawbone Flats to form the Little North Santiam River. Opal Lake occupies a cirque, and Opal Creek plunges over a series of three falls for a total drop in elevation of nearly 170 m. The upper falls is less than 0.25 mi northeast of the lake. The outcrops at this stop are bedded pyroclastic rocks that are probably rhyodacitic in composition. On the basis of White's (1980b) lithologic descriptions, similar stratigraphic position, and elevation, it appears that these rocks are part of the Elk Lake formation. The outcrops are well-layered, coarse heterolithic fragmental units of weathered, light-colored units interlayered with dark-colored, fragmental units of uniform clast types. The rocks are cut by a zeolite-coated fracture set that trends N. 40° W. and dips 70° SW. The fracture orientation is a common orientation encountered in the North Santiam mining area. The volcaniclastic rocks are intruded by subvolcanic intrusions that cut the bedding at various angles.

11.6 mi (1.2 mi) White (1980b) mapped the crest of French Creek Ridge as the Elk Lake formation unconformably overlying rocks of the Sardine Formation. The thickness of the Elk Lake formation is 150 m at this locality. White defined two members of the formation: the lower consists of rhyodacitic flows and pyroclastic rocks, the upper of one or more thick flows of hornblende andesite. The pyroclastic units of the lower member are white or pale-pink crystal-lithic tuff; flows are light gray and generally are flow banded. These lavas were probably erupted from a vent complex at the southwestern end of French Creek Ridge. This vent complex is the knob immediately southeast of the road at the crest of French Creek Ridge. White indicates that a small dome can be seen to intrude and to overlie the Sardine lavas at this point. A spine that is 10 m high occurs near the center of the dome. The upper member of the Elk Lake formation overlies the rhyodacitic rocks in the prominent knobs northeast of the pass at Martin Buttes and Byers Peak. These prominences are underlain by a single andesitic flow that is 60 m thick and that displays a prominent colonnade. The andesites contain abundant phenocrysts of plagioclase and less abundant but common phenocrysts of augite. Hypersthene and remnants of probable amphibole crystals are sparsely present as phenocrysts. The Elk Lake formation overlies both the Sardine and Breitenbush Formations with strong angular unconformity. Two K-Ar whole-rock ages for rocks of the Elk Lake formation are 9.8±0.46 m.y. and 11.8±0.4 m.y. (White, 1980b).

13.3 mi (1.7 mi) **Stop 9.** At this switchback, medium- to coarse-grained quartz diorite dikes intrude fine-grained ash beds of the Sardine Formation. Hydrothermal alteration around the dikes has produced zeolitic alteration of the tuffs. Near the contact, the replacement is extensive but decreases in intensity away from the contact where the development of zeolites becomes confined to fracture fillings and breccia cement. Analysis by X-ray diffraction indicates that laumontite is the main zeolite present. The contacts of the dikes are chilled against the wall, and xenoliths of tuff are incorporated into the dike. Abundant fine-grained xenoliths occur in the dike but, except for those near the contacts, are not derived from the immediate wall rocks. The contact strikes N. 10° W. and dips 75° NE. Feldspar phenocrysts are strongly fractured, suggesting shattering such as might occur during hydrofracturing. These intrusions were emplaced at shallow depths.

14.2 mi (0.9 mi) Overview of Sardine Mountain, the type locality of the Sardine series as defined by Thayer (1939). Sardine Mountain is an eroded vent complex. Thin flows, bedded cinders, and radial dikes are considered to be a typical vent-facies assemblage exposed on the northern and western sides of the mountain (White, 1980b). On Hall Ridge immediately south of Sardine Mountain, flows are generally porphyritic, containing abundant plagioclase phenocrysts and lesser amounts of mafic phenocrysts. Most of the andesites have hypersthene and augite as phenocrysts. Lava flows compose from 50 to 70 percent of the formation in areas away from the vent complex. The rest of the formation is composed of lahars and lapilli tuff.

18.4 mi (4.2 mi) Intersection with USFS Road 2223. *Continue straight ahead.* The sharp turn to the right would take you up Sardine Mountain to Tumble Lake.

18.6 mi (0.2 mi) Intersection with Oregon Highway 22. *Turn right to return to Salem or left to go to the towns of Detroit, Breitenbush Hot Springs, or Bend.* □

BOOK REVIEW

by Daniel M. Johnson, Associate Professor of Geography, Geography Department, Portland State University, Portland, Oregon 97207

The Legacy of Ancient Lake Modoc: A Historical Geography of the Klamath Lakes Basin, by Sam and Emily Dicken, published by the authors, available from the University of Oregon Bookstore, 895 E. 13th, Eugene, OR 97403, or Shaw Stationery Company, 792 Main St., Klamath Falls, OR 97601. Price $10.

For nearly 40 years, geographers Sam and Emily Dicken have been exploring and studying their adopted state of Oregon. They have shared the results of these efforts with the public through a series of books and journal articles, beginning with the first edition of *Oregon Geography* published in 1950. In recent years we have been treated to *Two Centuries of Oregon Geography: Vol 1., The Making of Oregon* (1979) and *Vol. 2, A Regional Geography* (1982). Their work on the historical geography of Oregon has now been continued in a newly published book entitled *The Legacy of Ancient Lake Modoc: A Historical Geography of the Klamath Lakes Basin* (copyright 1985 by the authors). This book represents a delightful blend of the two disciplines, but it differs from the Dickens' earlier work in that it focuses on one region of the state, the Klamath Lakes basin of south-central Oregon. It amounts to a chronological description of both natural and human features, beginning with the period of exploration in the early 19th century and continuing to 1985. Throughout, the authors have given careful attention to the perceptions of the region by those who explored and settled it.

In the first chapter, the Dickens present an overview by the interesting technique of escorting the reader on an imaginary airplane flight. Only from this lofty perspective can the unity of the Klamath Lakes region be appreciated. As they point out, the "unifying feature is the lake plain, the bed of Old Lake Modoc," a Pleistocene lake whose shoreline was drawn for the first time by Sam Dicken in an article in the November 1980 issue of *Oregon Geology*. Modern lakes of the region, including Oregon's largest (Upper Klamath Lake), are remnants of this larger Lake Modoc. *(Continued on page 10, **Book Review**)*

K-Ar AGES OF PLUTONISM AND MINERALIZATION, WESTERN CASCADES, OREGON AND SOUTHERN WASHINGTON

S. G. POWER, C. W. FIELD — *Department of Geology, Oregon State University, Corvallis, OR 97331*

R. L. ARMSTRONG, J. E. HARAKAL — *Department of Geological Sciences, University of British Columbia, Vancouver, British Columbia, Canada V6T 1W5*

The central and northern parts of the Cascade Mountains in Washington host numerous deposits of porphyry-type copper mineralization, illustrated in Figure 1, that are spatially and temporally associated with Tertiary batholithic intrusions (Grant, 1969 and 1976; Field and others, 1974; Armstrong and others, 1976; Hollister, 1979). To the south and into the Southern Cascades of Washington and the Western Cascades of northern and central Oregon, there are systematic changes in both the plutonic host rocks and their associated mineral deposits. The intrusions diminish from batholithic dimensions to stocks, plugs, and smaller tabular bodies, and the textural and compositional characteristics of associated mineralization change from relatively large deposits of disseminated copper (with minor molybdenum) to small and structurally controlled vein-type deposits of polymetallic base (copper, lead, and zinc) and precious (gold and silver) metals (Callahan and Buddington, 1938; Peck and others, 1964; Power and Field, 1981). Locations of these more southerly mining districts are also shown in figure 1, and it should be noted that recent exploration programs have documented the presence of disseminated porphyry-type copper mineralization at depth in the Washougal district of Washington and in the North Santiam district of Oregon (Moen, 1977; Power and Field, 1981).

In this report we present radiometric age determinations for plutonic rocks of the Washougal district (20 m.y.), North Santiam district (13 m.y.), Blue River district (13 m.y.), and the Bohemia district (22 m.y.), and for hydrothermal alteration of the Washougal district (19 m.y.). Peck and others (1964) previously estimated the ages of dioritic plutons in the Western Cascades of Oregon to range from Eocene to late Miocene. The age determinations we report indicate two well-defined episodes of plutonism and associated hydrothermal mineralization at about 13 and 20 m.y., respectively. They are broadly coincident with several episodes of volcanism that culminated at 12, 16, and possibly 22 m.y. in the central Cascade Range of Oregon, according to the data of McBirney and others (1974) and Armstrong (1975), and they fit within the spectrum of ages ranging from 6 to at least 24 m.y. for plutonism and associated porphyry-type mineralization in the Cascade Range of Washington as reported by Field and others (1974), and Armstrong and others (1976). The older episode (about 20 m.y.) that is represented by ages for mineralization and (or) plutonism in the Washougal and Bohemia districts is essentially identical to that of the Glacier Peak porphyry-type deposit (Field and others, 1974) and to early phases of the Tatoosh pluton (Mattinson, 1973) in Washington. The younger episode (13 m.y.), given by ages for intrusions of the North Santiam and Blue River districts, is similar to those ages obtained for later phases of the Tatoosh pluton (Mattinson, 1973). These results document the general contemporaneity of plutonic-hydrothermal events in the Western Cascades of Oregon to their counterparts in Washington. Moreover, they suggest by correlation and inference that porphyry-type copper deposits may be present at depth in the base and precious metal mining districts of the central Oregon Cascades.

Samples were collected by J. P. Olson, S. G. Power, M. P. Schaubs, and A. Schriener, Jr. The K-Ar age determinations were performed at the University of British Columbia. The general procedures for these analyses have been described by Armstrong and others (1976), and the analytical constants used are as follows:

$K_{\lambda_\epsilon} = 5.81 \times 10^{-11}$/y; $K_{\lambda_\beta} = 4.96 \times 10^{-10}$/y; and $^{40}K = 1.167 \times 10^{-4}$ atom percent.

Argon was determined by isotope dilution and potasium by atomic absorption spectrophotometry. The errors reported are for one standard deviation. Supplemental chemical and petrographic information for these samples may be found in Power and Field (1981) and references cited therein. This research has been funded by the Oregon Department of Geology and Mineral Industries and the Hanna Mining Company, and the generosity of both organizations is gratefully acknowledged.

SAMPLE DESCRIPTIONS

1. *WA-058A* K-Ar
Phyllic alteration (1680 ft elev. in Copper Creek near Black Jack Prospect in north-central part of unsurveyed portion of T3N,R5E, Washougal mining district, Skamania Co., WA). Granodiorite completely replaced by quartz, sericite, tourmaline, and pyrite. *Analytical data:* K = 4.62, 4.58%; $^*Ar^{40}$ = 3.414×10^{-6}cc/gm (65.1 %ΣAr^{40}).
(whole rock) 19.0 ± 0.7 m.y.

2. *WA-11* K-Ar
"Fresh" granodiorite (200 ft elev. near Black Ledge prospect, north-central part of unsurveyed portion of T3N,R5E, Washougal mining district, Skamania Co., WA). *Analytical data:* K = 1.90, 1.95%; $^*Ar^{40}$ = 1.476×10^{-6}cc/gm (25.2%ΣAr^{40}).
(whole rock) 19.6 ± 0.7 m.y.

3. *NS-11* K-Ar
"Fresh" granodiorite (3520 ft elev., SE¼ SE¼ S32,T8S,R5E, North Santiam mining district, Marion Co., OR). *Analytical data:* K = 0.370, 0.368%; $^*Ar^{40}$ = 0.1928×10^{-6}cc/gm (13.3%ΣAr^{40}).
(hornblende) 13.4 ± 0.9 m.y.

4. *BR-6* K-Ar
Quartz diorite (4200 ft elev. on ridge NE of Gold Hill, SE¼ NW¼ S32,T15S,R4E, Blue River mining district, Lane Co., OR). *Analytical data:* K = 0.837, 0.829%; $^*Ar^{40}$ = 0.4358×10^{-6}cc/gm (10.6%ΣAr^{40}).
(whole rock) 13.4 ± 1.2 m.y.

5. *BO-7* K-Ar
Quartz diorite porphyry (3720 ft elev. in Champion Creek, NE¼ SW¼ S12,T23S,R1E, Bohemia mining district, Lane Co., OR). *Analytical data:* K = 1.38, 1.35%; $^*Ar^{40}$ = 1.157×10^{-6}cc/gm (55.9%ΣAr^{40}).
(whole rock) 21.7 ± 0.8 m.y.