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The Geology of Quartz Creek:

Plutons, Copper Mineralization, and Alteration of the Snoqualmie Batholith, Cascade Range, Washington

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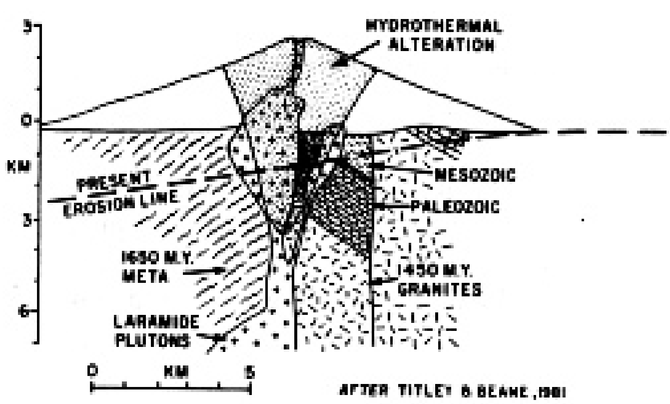


ABSTRACT

Porphyry ore deposits are submagmatic, disseminated zones of mineralization related to the tops of porphyritic felsic plutons. Porphyry copper mineralization and alteration (CMA) at Quartz Creek are superimposed on four igneous phases in the western part of the Miocene Snoqualmie batholith. Because the effects of weathering are minuscule and the rocks are mostly medium-grained, Quartz Creek provides an unusual opportunity to study batholithic rocks and CMA.

The major host for CMA is the medium-grained, equigranular, hornblende- and biotite-bearing Quartz Creek quartz diorite and its xe-nolithic, aphanitic to porphyritic border phase. Whatever pluton generated CMA is at some unknown depth. CMA is “inside-out” with respect to most porphyry copper deposits: per¬vasive biotitic alteration grades outward into fresh rock. The zone of biotitic alteration is elongate to the northwest (> 8400 feet) and open to the southeast, 2000 feet wide, and exposed over 1500 feet vertically. Magnetite in the outer part of the zone grades inward to pyrite, chalcopyrite, and molybdenite.

Superimposed on and inside the biotitic al¬teration is an irregular zone of chloritic alteration centered on two zones of quartz-sericite-pyrite alteration (QSP). The QSP, with chalcopyrite and tourmaline, is superimposed on two biotitically altered breccia pipes. The two QSP zones are < 450 feet by 200 feet (elongate to the NNE). The eastern pipe was drilled to a depth of 763 feet. In the eastern pipe, QSP also replaces andalusite and pyrrhotite. Pyrite dominates the eastern pipe; whereas, arsenopyrite dominates the western pipe.

Quartz Creek is a quartz-dioritic, batholithic, copper-molybdenum representative of porphyry ore deposits. It is similar to the quartz monzo-nitic, batholithic, copper-molybdenum deposit at Butte, Montana. Quartz Creek was last explored in the mid-1960s before models of porphyritic or batholithic deposits were well known. Steep topography, lack of weathering, the low grade and tonnage of mineralized rock at the surface, and a potentially hostile political climate deter development.

INTRODUCTION

PURPOSE

This field trip inspects several igneous phases of the mid-Miocene Snoqualmie Batholith at the Quartz Creek copper prospect in the western part of the batholith and examines the hydrothermal alteration and mineralization at the prospect. Lack of weathering, the generally medium-grained size of the intrusive rocks, and easy access make Quartz Creek an ideal place to observe the effects of magmatic and hydrother-mal processes.

ITINERARY

The Quartz Creek copper prospect is about 36 miles (58 km) east of Seattle in the Snoqualmie batholith. Specifically, most of the prospect is in N/2 Section 16 of T24N, R1OE; this area is on the Lake Phillippa (1989) 1:24,000 USGS topographic map.

The first stop of the trip is the Snoqualmie Winery for an overview of the regional geology (Figure 1). To reach the winery take Exit 27 (eastbound) off Interstate 90; no corresponding westbound exists. At the exit turn right and follow the road around to the left for about 1/3 mile to the gate of the winery. The view eastward from the winery is approximately along the arrow in Figure 1 that labels the Snoqualmie batholith. The most conspicuous geomorphic features are the flat-topped remnants of the lateral moraine of the Puget lobe that advanced up the South Fork of the Snoqualmie River (the route of 1-90) and up the Middle Fork (the site of Quartz Creek). The crest of the moraine is 1680 feet; whereas, the valley in front is 600 feet. The ice and moraine dammed lakes in both the South and Middle Forks of the Snoqualmie.

Access to Quartz Creek is from Exit 34 of I-90. From this exit proceed north about 13.0 miles on 468th Ave. SE, SE Middle Fork Road, and the Taylor River Road to the bridge on the Taylor River at the present end of the road.

The main part of the trip is a five-mile (round-trip) walk (over 95% on logging roads) from the bridge up the valley of Quartz Creek. The maximum vertical ascent of this walk is 1400 feet. This part of the trip will take four or five hours. Bring your lunch (and rain gear?). Specific stops are neither described nor shown, but can be located on the accompanying maps.

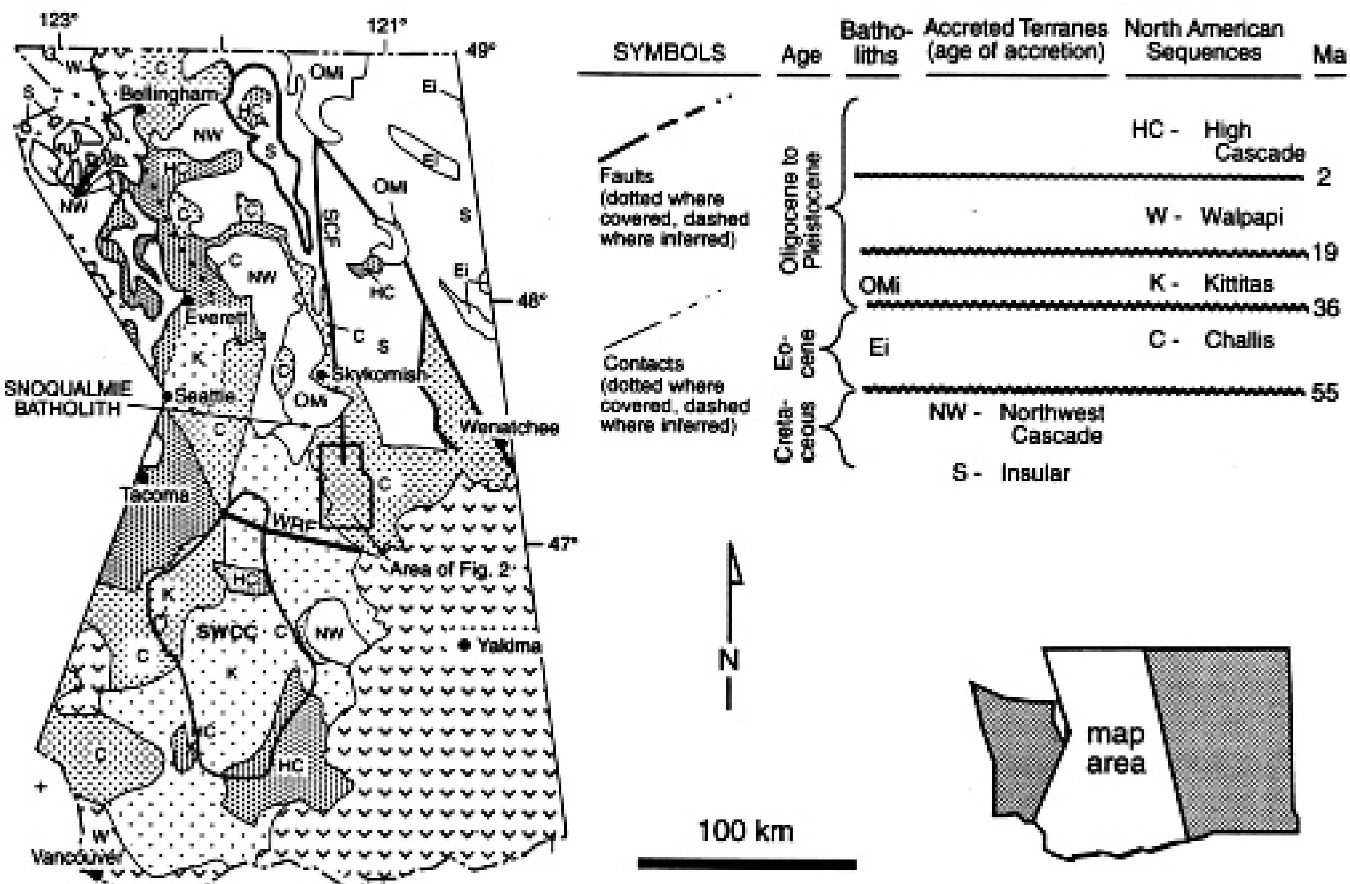


Figure 1. REGIONAL GEOLOGY OF CENTRAL WASHINGTON.

The Snoqualmie batholith is the southern portion of the indicated area labeled OMi (see Fig. 3). Modified from Cheney (1994, fig. 10).

PORPHYRY ORE DEPOSITS

Because Quartz Creek is a porphyry copper deposit, a brief review of that kind of ore deposit may be useful (cf. Titley and Beane, 1981). Porphyry ore deposits are zones of disseminated, post-magmatic (i.e., hydrothermal) mineralization related to the tops of felsic intrusions. They are disseminated in the sense that individual mineralized structures are too small or narrow to mine individually and, thus, the entire zone of mineralized rock is mined. However, almost all of the mineralization is on (or related to) fractures (or former fractures) in the rock. The most common ore minerals are chalcopyrite, bomite, and molybdenite; gangue (non-ore) minerals are pyrite, anhydrite, magnetite (or hematite), fluorite, and various silicate minerals. The fluids that deposited the mineralization also altered the original rocks. This alteration commonly is more voluminous than the zone of even subeconomic mineralization; thus, the mapping and understanding of zones of hydrothermal alteration are prime methods of discovering and geologically evaluating a porphyry ore system.

Hydrothermal (250 to 750°C) alteration and mineralization are termed hypogene ("origin from below"). In mostporphyry copper deposits, hypogene mineralization is < 0.5 to £ 0.8% Cu and is usually subeconomic Most deposits are economic due to chemical weathering which, as the deposit was being eroded, leached copper and iron from the hypo-gene mineralization and redeposited them at or below the water table as a blanket-like zone of sooty chalcocite and sooty marcasite. The effects of weathering are termed supergene ("origin from above")- Supergene sulfide blankets commonly cause enrichment two to six times the hypogene grade. The acidic waters associated with supergene enrichment partially or completely destroy the hypogene mineralogy, making the identification of rocks difficult on the surface of most porphyry ore systems.

Porphyry ore deposits are the mainstay of the copper industry in the Western Hemisphere, from Chile to British Columbia. Although porphyry copper deposits can be of very limited tonnage, economic ones range from a few hundred million tonnes to two billion tonnes of ore. Daily production varies from 104 to 10s tonnes/ day of ore and of waste. A few deposits produce 0.4% Cu. Average grades in U.S. deposits are 0.7% Cu, whereas foreign deposits are 0.8 to 2% due to supergene enrichment blankets.

Porphyry copper deposits commonly produce significant byproduct Mo, Ag, or Au. In some cases these elements are recovered in such small amounts they are termed "credits"; other credits can (or have been) U, platinum-group elements, and nickel. Due to air pollution controls, S is recovered (mainly as HjSC^) during smelting, as are Se and As. Porphyry Mo deposits are the major source of that metal. A very limited number of porphyry ore deposits recover (or have recovered) one of the following as the major product: Sn, W, Au, U, and F. The Quartz Creek deposit is a quartz-dior-itic, batholithic member of the greater group of porphyry ore deposits. Specifically, the hydrothermal alteration of batholithic deposits tends to be less intense and to have a different zonation than deposits centered on porphyritic stocks.

Mining engineers, accountants, and non-geological managers have a different definition of a porphyry ore deposit. To them, it is any large, low-grade, deposit that can be mined by bulk methods (such as 100- to 200-ton trucks), no matter what the rock-type, product, or origin of the deposit.

HISTORY OF QUARTZ CREEK

Minor production from the east breccia pipe at Quartz Creek occurred in the 1950s (Livingston, 1971). A shaft was sunk to 116 feet, and a 45 tonnes/day mill operated from 1951 to 1954. According to Livingston (1971), 363 tons (330 tonnes) of concentrate smelted from 1952 to 1956 averaged 17.6% Cu, 0.93% opt Ag and 0.26 opt Au.* Samples of drill core in the east breccia pipe were a maximum of 11.2%Cu,4.63opt Ag,0.16optAu,butl9of21 samples of well mineralized rocks had < 1/2 as much copper < 5/6 as much silver and < 1/2 as much gold as the maximum values (Livingston, 1971, figs. 98 and 99).

During the exploration boom for porphyry ore deposits in the 1960s, Quartz Creek was examined by several companies and was drilled in 1966. Howard (1967) and Rasrikriengkrai (1971) described the results of the last major exploration program. However, these exploration efforts and theses occurred before the geologic models of porphyry ore deposits, and especially their batholithic variety, were well developed. Renewed exploration in the early 1970s managed to destroy the mill and to bulldoze the dumps.

Since 1970, Quartz Creek has been used as mapping exercise for students of economic geology at the University of Washington. An unfortunate side effect has been that some of these students, acting as teaching assistants, have taken laboratory sections of introductory geology classes to Quartz Creek; the result is that good samples are now extremely difficult to find on the dump.

REGIONAL GEOLOGY

STRATIGRAPHY AND STRUCTURE

Figure 1 shows the regional geology of central Washington. The Snoqualmie batholith is one of the sources of the informally named Kittitas sequence (Cheney, 1994) of Oligocene to mid-Miocene volcanic and volcaniclastic rocks. The batholith is intrusive into the pre-Cenozoic accreted rocks of the Northwest Cascade superterrane, the Challis stratigraphic sequence of Eocene rocks, the Straight Creek fault, and the Kittitas sequence. Because of the regional southward dip, the

*Opt = troy ounces/ton. One troy ounce = 31.1 grams. One gram/metric tonne = 1 ppm.

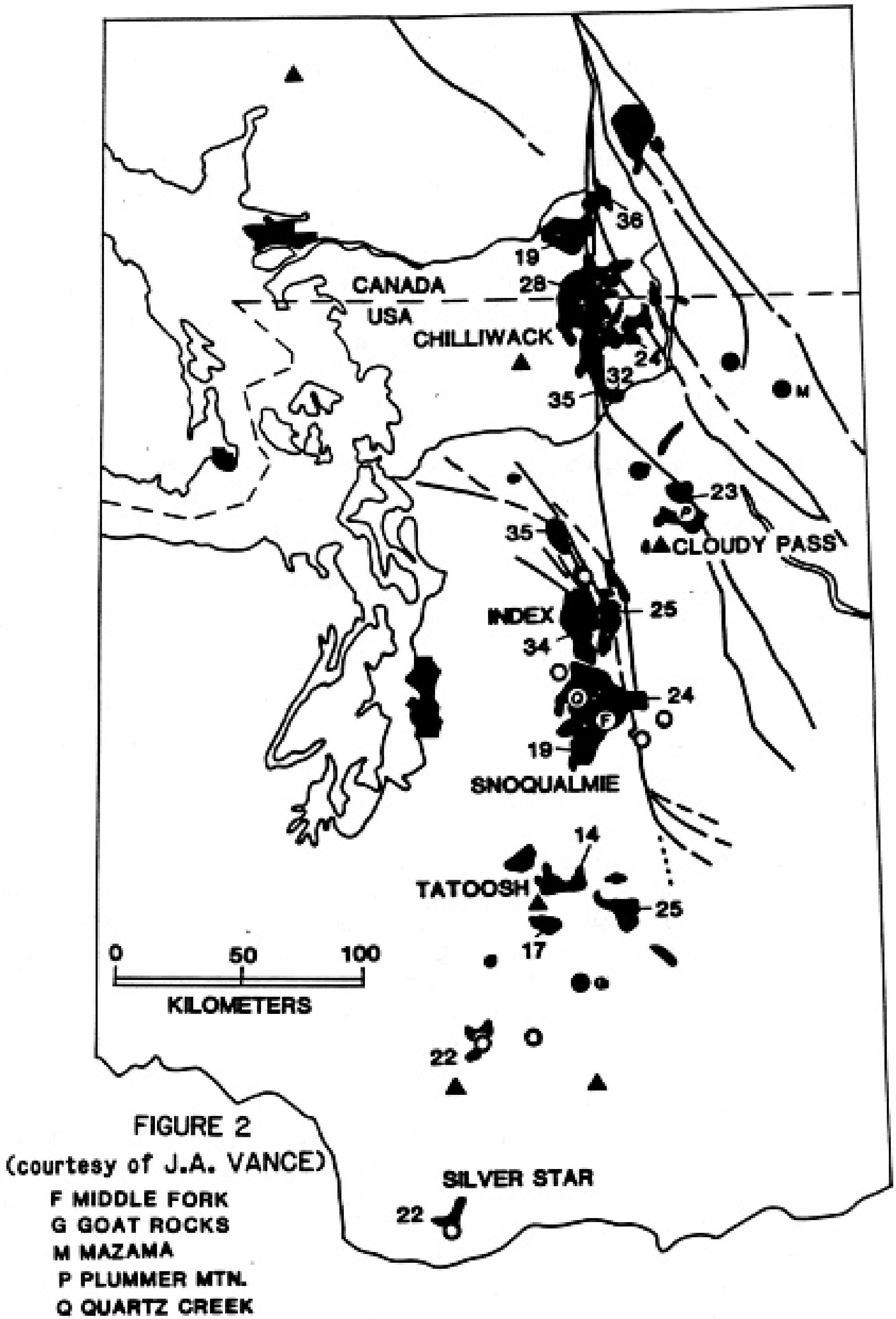


Figure 2. OLIGO-MIOCENE PLUTONS IN THE CASCADE RANGE.
Numbers in the figure are radiometric ages (nearly all determined prior to 1985) of the plutons. Filled circles are pre-Cenozoic porphyry ore systems. Open circles are Cenozoic porphyry ore systems.

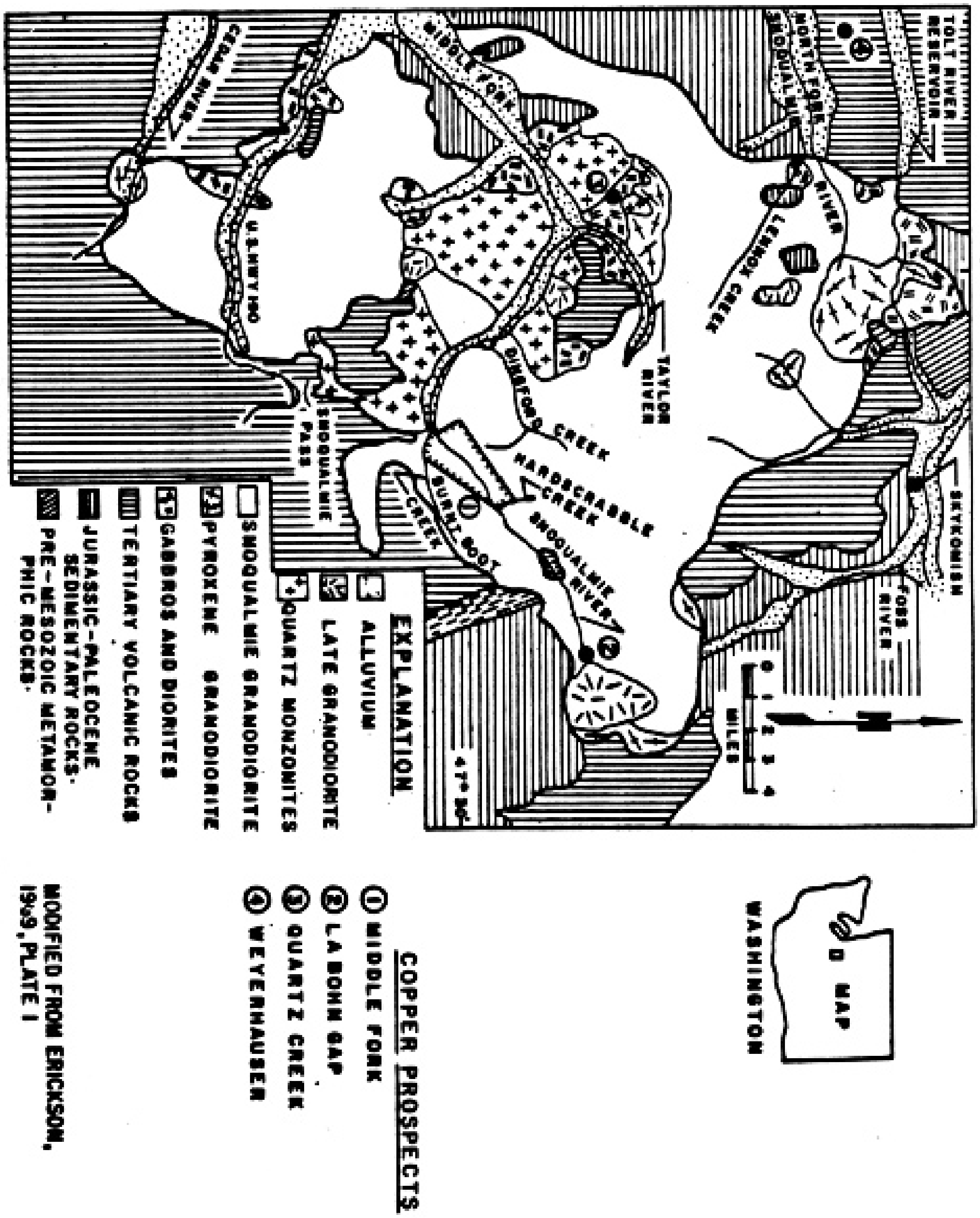


Figure 3: Geologic Map of the Snoqualmie Batholith

Kittitas sequence is now largely preserved south of the Snoqualmie batholith; whereas, older rocks are preserved mostly to the north.

The Walpapi sequence, the most voluminous lithostratigraphic unit of which is the Columbia River Basalt Group, is not preserved along the crest of the Cascade Range. In the vicinity of the Snoqualmie batholith the post-2.0 Ma High Cascade sequence is represented by various glacial units.

SNOQUALMIE BATHOLITH

Figure 2 shows that the Snoqualmie batholith is but one of many Kittitas-aged plutons in the Cascade Range. These plutons define an axis that strikes slightly west of the topographic axis of the present Cascade Range. Because this topographic axis is due to post-2.0 Ma uplift, it is genetically unrelated to the Kittitas-aged plutons.

Figure 3 is a geologic map of the Snoqualmie batholith, modified from Erikson (1969). A comparison of this map with Figure 1, which in the vicinity of the batholith is largely based on Frizzell et al. (1984) and Tabor et al. (1993), indicates that much has been learned about the country rocks since 1969. The important generalities to be gleaned from Figure 3 are, like so many batholiths, this one is (1) composite, with the younger phases tending to be the more felsic, and (2) because the batholith is intruded into Kittitas rocks of essentially its own age, it was hypabysally emplaced (and barely has been unroofed by erosion).

K-Ar ages reported for the batholith range from -25 to ~ 18 Ma (Frizzell et al., 1984; Tabor et al., 1993), with the younger ages possibly having been reset by younger phases of the batholith (Tabor etal., 1993). For example, ages for the Quartz Creek quartz diorite reported by Tabor et al. (K-Ar on hornblende is 25.6 ± 10 Ma; K-Ar on biotite is 20.5 ± 0.5 Ma) are from the zone of hydrothermal biotitic alteration described below.

A number of copper prospects occur in or near the batholith (Fig. 3). The Middle Fork prospect, which is geologically similar to Quartz Creek, was described by Patton et al. (1973). The La Bohn Gap prospect consists of veins in otherwise unaltered batholithic rock; proposed development of this prospect in the late 1960s was the cause celebre for establishing the Alpine Lakes Wilderness Area. Quartz Creek, which is not in the Wilderness Area, is described here. The porphyry deposit on the North Fork of the Snoqualmie River is described by Newport etal. (1994).

BATHOLITHIC GEOLOGY AT QUARTZ CREEK

INTRODUCTION

Figure 4 shows the geology of the Quartz Creek area. The area is underlain by four phases of the batholith and a roof pendant of volcanic rocks. Howard (1967), Fjickson (1969), and Rasrienkrienrai (1971) are the sources of the petrographic descriptions given below.

Porphyry ore systems commonly contain several intrusive phases that can be so similar that it is difficult to determine which intrudes which; these have been termed “incestuous complexes” (Wallace, 1974). At Quartz Creek, mapping of dikes, xenoliths, xenocrysts, and chilled margins indicates the relative ages shown in Figure 4.

HORNFELS

On the north side of Quartz Creek is an outlier of the roof pendant that underlies Mount Garfield, between the Taylor River and the Middle Fork of the Snoqualmie River (Fig. 3). The dark color of this volcaniclastic rock is probably due to contact metamorphism. This rock probably is part of the Kittitas sequence (Tabor etal., 1993).

PREACHER MOUNTAIN QUARTZ MONZONITE

The oldest intrusive phase at Quartz Creek is the Preacher Mountain Quartz Monzonite. This is a medium-grained, mostly equigranular rock, characterized by rounded to subangular quartz grains. Quartz is about 40%; hornblende and biotite total less than 5% of the mode. In thin section, the Preacher Mountain has abundant inters tital mymekitic intergrowths.

QUARTZ CREEK QUARTZ DIORTTE

The Quartz Creek quartz diorite is a hornblende plus biotite rock with two phases. The interior phase is medium-grained and equigranular with angular quartz grains. The quartz is up to about 20% but difficult to see megascopically. The border phase ranges from fine-grained equigranular to porphyritic (quartz and feldspar); the border phase characteristically has 1 to 60% xenoliths. Rounded quartz grains in the matrix probably are xenocrysts from the Preacher Mountain. Where xenoliths are abundant, the matrix of the border phase varies in a single outcrop. Quartz Creek quartz diorite is the main host for the CMA.

MAIN PHASE QUARTZ DIORTTE

An equigranular quartz diorite is chilled against the Quartz Creek and Preacher Mountain phases. It has subequal amounts of hornblende and biotite and about 30% quartz. This is probably the medium-grained main phase of the batholith.

UNNAMED BIOTITIC QUARTZ MONZONITE

A predominantly equigranular, biotitic quartz monzonite intrudes the other phases. Students who have mapped felsic xenoliths of Preacher Mountain quartz monzonite in dark Quartz Creek quartz diorite are dismayed to find xenoliths of dark Quartz Creek quartz diorite in a felsic matrix and, hence, have used various terms of endearment (including incestuous) for these rocks. However, this youngest phase has more biotite than hornblende and does not contain well rounded quartz grains, at least not in most outcrops. Quartz

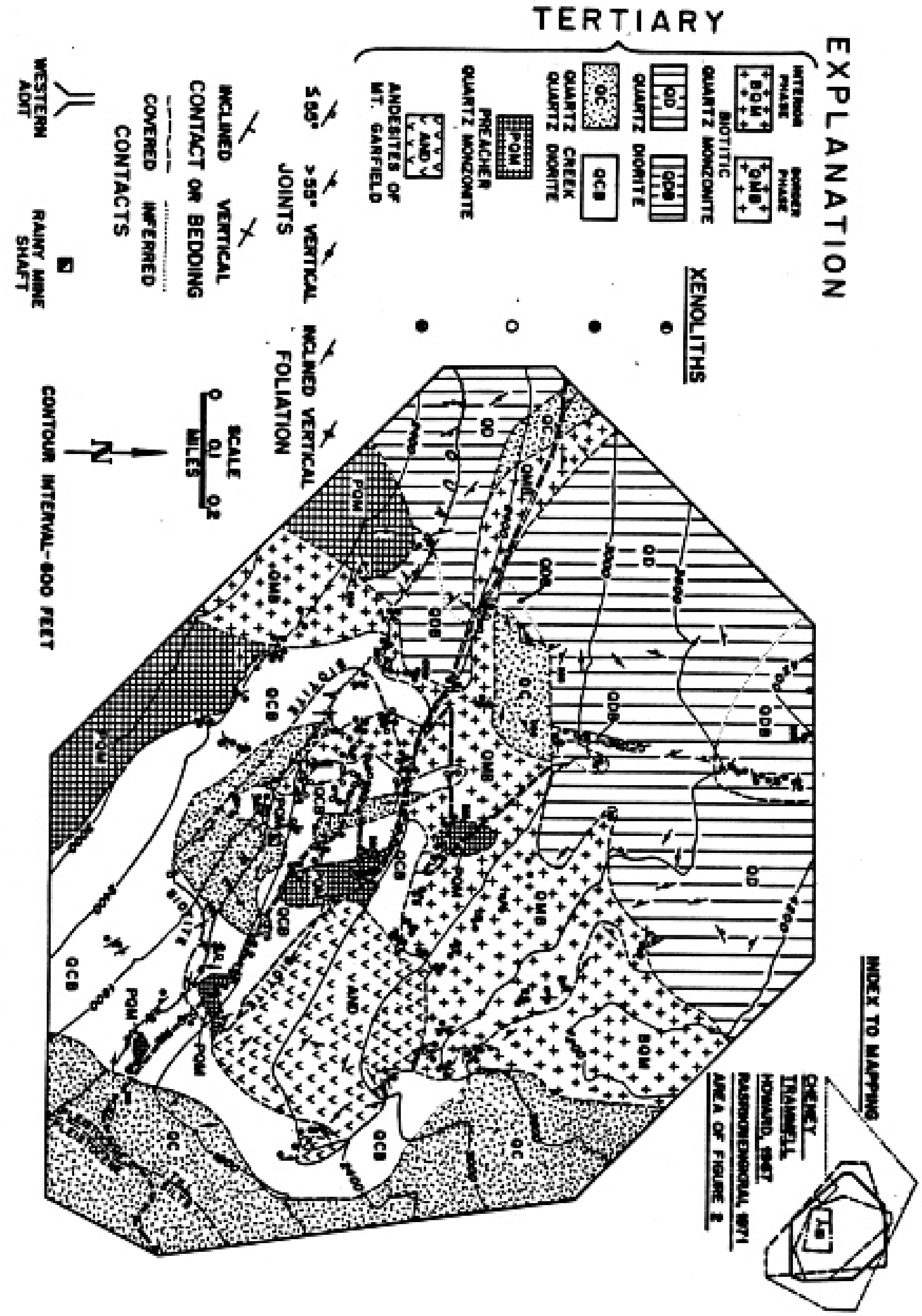


Figure 4: Geology of the Quartz Creek Area

is about as abundant as in the main phase of the batholith. This quartz monzonite could be a peripheral phase of themain phase.

Even this youngest phase is hydrothermally altered and mineralized. Thus, if a separate porphyritic phase of the batholith is responsible for the CMA (as is true in almost all porphyry ore systems), it is not exposed at the present level of erosion.

HYDROTHERMAL ALTERATION

INTRODUCTION

Quartz Creek has two temporally, spatially, and mineralogically distinct assemblages of hydrothermal alteration. The early biotitic alteration, generally with less than 1 % sulfide minerals, is the earlier and more extensive. Quartz + sericite + iron sulfide/arsenide (QSP) is limited to breccia pipes, and hosts the high-grade mineralization mined in the past. Chloritic alteration surrounds QSP but is within the biotitic alteration.

These three major types of alteration are common in porphyry ore systems. However, the zonation of these assemblages at Quartz Creek is distinctly different than in most porphyritic ore systems.

BIOTTTIC ALTERATION

Figures 4 and 5 partially define the area of biotitic alteration. Biotitic alteration is the replacement of igneous mafic minerals by apha-nitic to fine-grained biotite. Megascopically the sites of former igneous mafic minerals have neither good cleavage nor sharp outlines: they consist of an aggregate of felty or "fuzzy" biotite. Unfortunately, igneous petrographers describe this alteration as "deuteric."

Biotitic alteration is most conspicuous in comparatively mafic rocks, such as quartz diorites. In leucocratic rocks, such as quartz monzonites, alteration of igneous feldspars to hydrothermal K-feldspar tends to be more conspicuous.

In the outer part of the biotitic zone, fuzzy biotite is accompanied by magnetite (derived from the destruction of the original mafic minerals). In the outer part of the zone not all of the mafic minerals are altered (or fuzzy) and no sulf ide minerals occur. In the interior part of the biotitic zone, which is limited to the area of Figure 5, the rocks are sulfidic (pyrite + chalcopyrite + molybdenite) and less magnetic.

The biotite zone in Figure 5 is mostly the interior part of the zone. The outer limit of the interior zone is about 0.1% disseminated and fracture-controlled sulfides and is marked by limonitic weathering. Within the interior part of the zone, virtually all of the mafic minerals are fuzzy. A few outcrops outside the area of Figure 5 do have > 0.1% sulfides.

Biotitic alteration is more extensive than outlined in Figure 4, in which the southeastern portion of the biotitic zone terminates in the border phase of the Quartz Creek quartz diorite. The problem is that hydrothermal biotite is difficult to map in fine-grained rocks. However, the outer zone of the biotitic alteration does occur in the medium-grained, interior phase of the Quartz Creek quartz diorite in the southeastern corner of Figure 4, and it extends at least as far southeast as the bridge across the Taylor River.

From surface mapping the outer zone of biotitic alteration is, therefore, > 8400 feet (2600 m) northwesterly, 2000 feet (660 m) southwesterly, and is exposed over a vertical interval of 1460 feet (480 m). By comparison, the world-class batholithic copper deposit at Butte, Montana (which has been extensively sampled in the subsurface) has a domal-shaped biotitic zone > 20,000 feet long, 6500 feet wide, and is £ 3000 feet in the vertical dimension (Roberts in Miller, 1973); however, 2000 feet above these maximum dimentions, the biotitic zone is only 16,000 feet long and 4000 feet wide. Thus, Quartz Creek is a significant hydrothermal system.

MAFIC-DESTRUCTIVE ALTERATIONS

Whereas biotitic alteration causes recrystallization of the mafic minerals, the younger, less extensive alterations are mafic-destructive, resulting in "bleached" rock. Locally, biotitically altered rock is pervasively altered to quartz-sericite-pyrite(QSP). Microscopically (and even, locally, megascopically) some of the mica is coarse-grained enough to identify as muscovite, so the fine-grained colorless mica in thin section most likely is, truly, sericite. Chalcopyrite and tourmaline are parts of this assemblage.

Pervasive QSP is restricted to portions of two breccia pipes, and these zones are elongated to the NNE (Fig. 5). The major portion of the eastern pipe has no QSP, implying that the pipe formed during biotitic alteration and subsequently was partially converted to QSP. Look for samples on the dump in which clasts of biotitically altered rock are rimmed or cut by QSP.

The Hemley-Jones diagram of Figure 6 shows that QSP occurs at a lower temperature and/or lower K+/H+ than feldspathic (or biotitic) alte¬ation. Investigations of other porphyry ore systems show that biotitic (or feldspathic) alteration typically formed at 400 to 750°C from saline solutions derived magma, whereas QSP is generally < 400°, precipitated from less saline solutions, and was derived from meteoric water (Titley and Beane, 1981).

A mafic-destructive alteration older than QSP occurs in the eastern breccia pipe. Rare examples exist of quartz-sericite pseudomorphic after euhedral andalusite up to a few centimeters long. Unaltered andalusite only occurs within massive pyrrhotite; whereas, serialized anda¬lusite is in pyritic rock. The Hemley-Jones diagram (Fig. 6) indicates that the hydrothermal solutions that caused the andalusite had a lower K+/H+, and possibly a higher temperature than QSP. The presence of pyrrhotite, rather than pyrite, indicates that

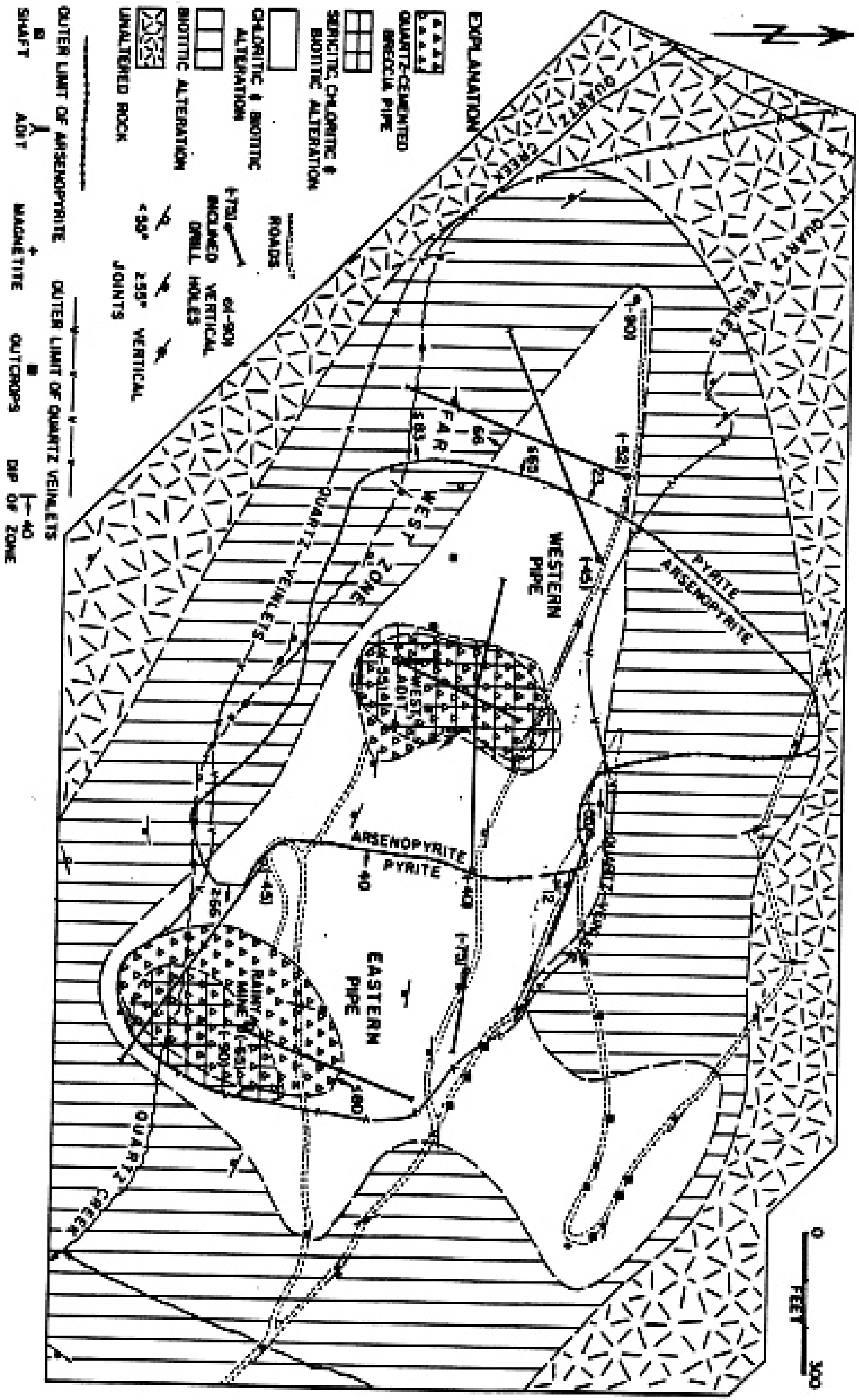


Figure 5. HYDROTHERM AL ALTERATION AND MINERALIZATION IN THE VICINITY OF THE BRECCIA PIPES AT QUARTZ CREEK

the andalusitic alteration occurred at a lower fs2 than QSP.

CHLORITIC ALTERATION

Figure 5 shows that zones of QSP are surrounded by a chloride zone. This zone is mostly characterized by sparse veins surrounded by mm-scale chloritic envelopes in biotitically altered rock. Locally, however, especially in drill core, pervasive fuzzy biotite is replaced by pervasive fuzzy chlorite. This chloritic zone is akin to the zone of propylitic alteration (chlorite + epidote + calcite + albite + pyrite) that sur¬rounds most porphyritic ore deposits.

SUMMARY

Figures 5 and 7 show that the alteration at Quartz Creek is “inside-out” (Cheney et al., 1972) with respect to the alteration zones described by Guilbert and Lowell (1974) for most porphyry ore deposits. At Quartz Creek, biotitic alteration grades outward into unaltered rock, not outward into propylitic alteration; further¬more, QSP occurs inside the biotitic alteration. These are characteristics of batholithic systems, as opposed to porphyritic ore systems centered on stocks (Cheney and Trammell, 1973). Assuming that QSP was due to the ingress of meteoric water as the magmatic hydrothermal system collapsed, ingress of meteoric fluids into batholiths (which cool more uniformly) seems to be limited to discrete structural features, such as faults at Butte and breccia pipes at Quartz Creek.

HYDROTHERMAL MINERALIZATION

The sulfide minerals indigenous to biotitically altered rock are pyrite, chalcopyrite, and molybdenite. In contrast to the great extent of the outer zone, the interior (sulfidic) zone of biotitic alteration is about 2000 by 1000 feet (670 by 335 m). At the surface, most of this biotitically altered rock is < 0.1 % Cu with a trace of Mo. Optimistically, only the top of the sulfide zone is exposed, and it becomes larger, more sulfidic, and more cupriferous with depth. Significantly, all previous mine workings are in QSP. Clearly, the content of chalcopyrite in the sericitically altered portions of the breccia pipes is greater than in presently exposed biotitically altered rock, probably by at least an order of magnitude. A vertical drill hole in the eastern pipe was 763 feet deep (Rasrikriengkrai, 1971). Most of the drill holes were oriented to test the extent and copper content of the breccia pipes (which are partially sericitically altered). However, it is clear from Figure 7, Butte, Montana, and other porphyry ore deposits that the greatest tonnage of copper and molybdenum mineralization is in biotitically altered rock, which was not well tested at Quartz Creek by drilling in the 1960s.

Figure 5 shows that the eastern and western breccia pipes have different mineralogies and therefore, presumably represent different periods of QSP alteration. The western breccia pipe has arsenopyrite (for which a penalty would be assessed during smelting), but no pyrite; whereas, the eastern pipe has pyrite but no arsenopyrite. The relative ages of these two sulfide assemblages is not known.

STRUCTURE

Although the zone of biotitic alteration and the zone of quartz veinlets are elongate to the northwest, the causes of these elongations are unknown. If they are due to an unexposed elongate porphyritic stock at depth, the cause of that elongation is unknown.

The most obvious structures are the breccia pipes. The control(s) on their emplacement and NNE elongation are unknown.

The most prominent joints strike WNW. The valley of Quartz Creek is typically U-shaped above 2200 feetand V-shaped below. The mouth of this original hanging glacial valley has been lowered to the altitude of the Taylor River (~ 1100 feet). Below 2200 feet the rocks at Quartz Creek are cut by prominent, steep, valleyward dipping joints. These NNW joints are due to exfoliation caused by the post-glacial downcutting of Quartz Creek.

PLEISTOCENE GEOLOGY

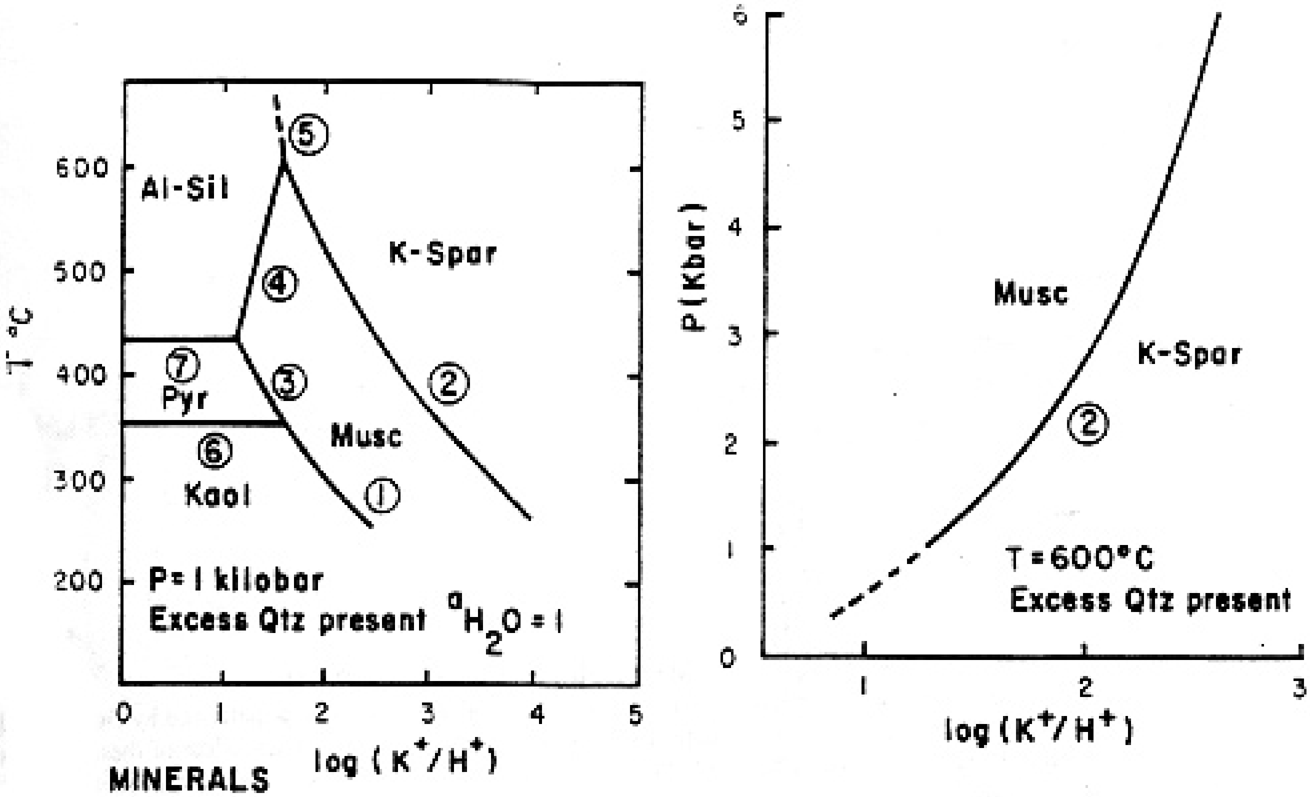
Lacustrine silts formed behind the lateral moraine of the Puget Lobe that dammed the Middle Fork of the Snoqualmie River near 1-90; these silts extend to about 1600 feet at Quartz Creek. Above these silts is glacial till (south¬eastern corner of Figure 4). Ice-rafted clasts and slump features occur in the silts along the access road to Quartz Creek.

These silts have important engineering implications. Former plans to build a dam across the Middle Fork were abandoned, at least in part, because the silts would have slumped continuously into the reservoir. If the Quartz Creek deposit were to be developed on a significant scale, the mine buildings, dumps, and tailing ponds might have to be constructed on these silts.

Before logging and mining operations began, most of the mineralization at Quartz Creek was overlain by glacial till. This prevented any significant weathering of even sulfidic rocks. Thus, unlike most porphyry systems elsewhere in the United States, even minute grains of sulfides remain in outcrops.

SUPERGENE ENRICHMENT

Most economic porphyry ore deposits started in supergene sulfide enrichment blankets. Weathering of sulfidic rocks at Quartz Creek is virtually nil. Thus, no supergene enrichment should be expected. Furthermore, supergene enrichment only occurs where the groundwater remained acidic enough (due to the oxidation of pyrite) to keep copper in solution and to transport it downward. The paucity of QSP at Quartz Creek shows that meteoric waters would not have been acidic enough to cause supergene enrichment, even if extensive weathering had occurred (cf. Fig. 6).



MINERALS

Al_2SiO_5 (kyanite, andalusite, or sillimanite) (Al-Sil) SiO_2 (Quartz) (Qtz)

$Al_2Si_4O_{10}(OH)_2$ (pyrophyllite) (pyr) $Al_4Si_4O_{10}(OH)_8$ (kaolinite) (kaol)

$KAl_3Si_3O_{10}(OH)_2$ (muscovite) (musc) $KAlSi_3O_8$ (potassium feldspar) (K-spar)

REACTIONS

(1) 3Kaol + $4K^+$ ⇌ 4Musc + $6H_2O$ + $4H^+$

(2) Musc + 6Qtz + $2K^+$ ⇌ 3K-spar + $2H^+$

(3) 3Pyr + $2K^+$ ⇌ 2Musc + 6Qtz + $2H^+$

(4) 3Al-Sil + 3Qtz + $3H_2O$ + $2K^+$ ⇌ 2Musc + $2H^+$

(5) Al-Sil + 5Qtz + H_2O + $2K^+$ ⇌ 2K-spar + $2H^+$

(6) Kaol + 4Qtz ⇌ 2Pyr + $2H_2O$

(7) Pyr ⇌ 3Qtz + Al-Sil + H_2O

METASTABLE REACTIONS

(8) Kaol + 8 Qtz + $4K^+$ ⇌ 4K-spar + $2H_2O$ + $4H^+$

(9) Pyr + 2Qtz + $2K^+$ ⇌ 2K-spar + $2H^+$

Figure 6. HEMLEY/JONES DIAGRAM SHOWING THE STABILITY FIELDS OF COMMON HYDRO-THERMAL MINERALS. In this diagram, K-spar is the proxy for biotitic alteration. Modified from Hemley and Jones (1964) by R. L. Gresens in 1981.

None of the porphyry ore systems in the Cascade Range (Fig. 2) have been mined on a significant scale. A decision to produce the deposit at Plummer Mountain in the Cloudy Pass pluton was abandoned after the Glacier Peak Wilderness Area was declared around it in the 1960s. Lack of production of the porphyry deposits of the Cascade Range is not just due to the hostile political climate, but is primarily due to the lack of significant supergene enrichment since the last glaciation.

TYPES OF PORPHYRY ORE DEPOSITS

Figure 8 shows that porphyry ore deposits are subdivided according to the major com¬mercial metal, composition of the host pluton, and whether the host pluton is a porphyritic stock or a batholith. Value-wise quartz dioritic porphyry copper systems tend to produce more byproduct gold than molybdenum; whereas, quartz monzonitic plutons produce more byproduct Mo (and usually lesser values of gold). Quartz monzonitic copper deposits and porphyry Mo deposits occur above sialic crust. Quartz dioritic plutons are common in island arcs and accreted terranes. In the Pacific Northwest (Fig. 9), the western edge of the pre-Phanerozoic sialic basement of North America is represented by the abrupt change in the initial 87Sr/86Sr ratio of Mesozoic plutons from 0.704 to 0.706 (Armstrong etal., 1978). Quartz diorite porphyry ore systems are west of this line; all known porphyry Mo deposits, and the quartz monzonitic Cu deposit at Butte, Montana, are east of the line.

Quartz Creek is a quartz dioritic, batholithic copper deposit without supergene enrichment. Its gold content is unevaluated.

EVALUATION

Although Quartz Creek was last explored before models of porphyritic and batholithic copper deposits were well understood, the following suggest that it is likely to remain uneconomic:

1) The probability of supergene enrichment is nil.

2) Because of the narrowness of the valley, underground mining would be required.

3) Ore-grade mineralization does not occur at the surface. If it occurs at depth, underground mining would be even more likely.

4) The space available for dumps of waste rock and for the disposal tailings is severely limited by the topography and the political climate. If underground mining does occur, some of the waste and tailings might be used as backfill in the mine.

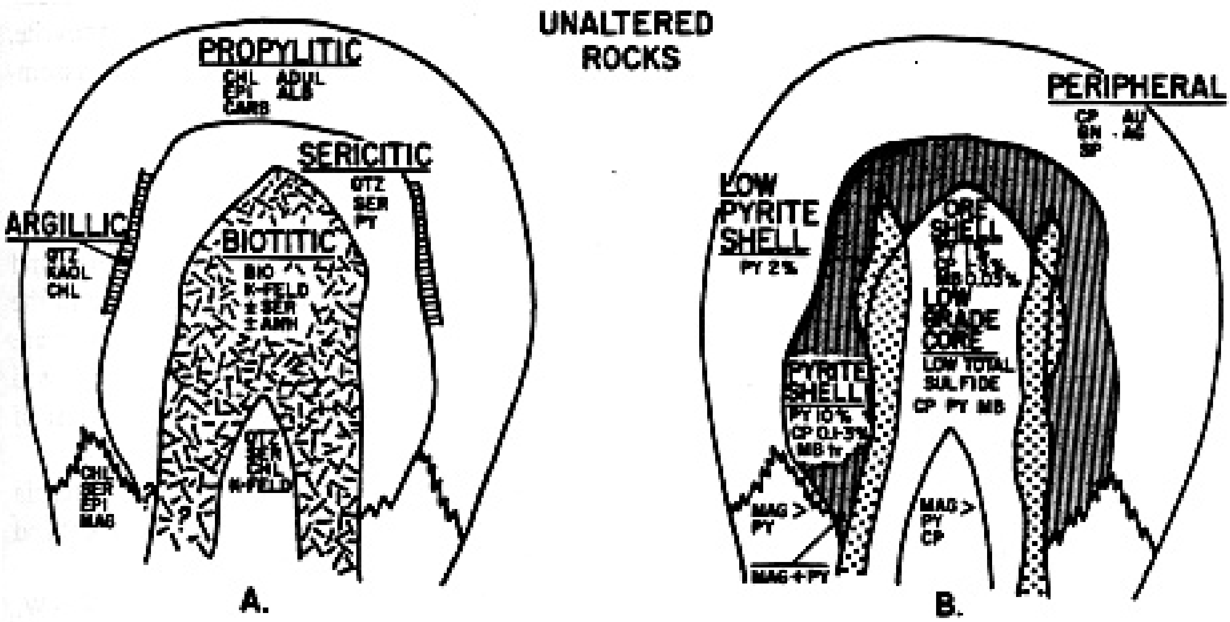
Because underground mining is more expensive than surface mining, correspondingly higher ore grades are needed. Due to economies of scale, larger underground mines can work lower grades of ore than small mines. At present prices, a large underground copper mine would require 107 to 108 tonnes of at least 1% Cu. An underground gold mine would require 106 to 107 tonnes of about 6 grams of Au/tonne (6 ppm Au).

An interesting comparison for Quartz Creek is the underground Kalamazoo porphyry ore deposit currently being developed in Arizona. The deposit (Magma Copper Company, 1994) has 169 million metric tonnes of 0.652% recoverable (mineable and diluted) copper. The viability of Kalamazoo is enhanced bycurrent surface and underground mining of the nearby San Manuel porphyry copper deposit. Even so, the anticipated capital cost of Kalamazoo is approximately $140 million. The planned production rate is 45,000 tonnes/day.

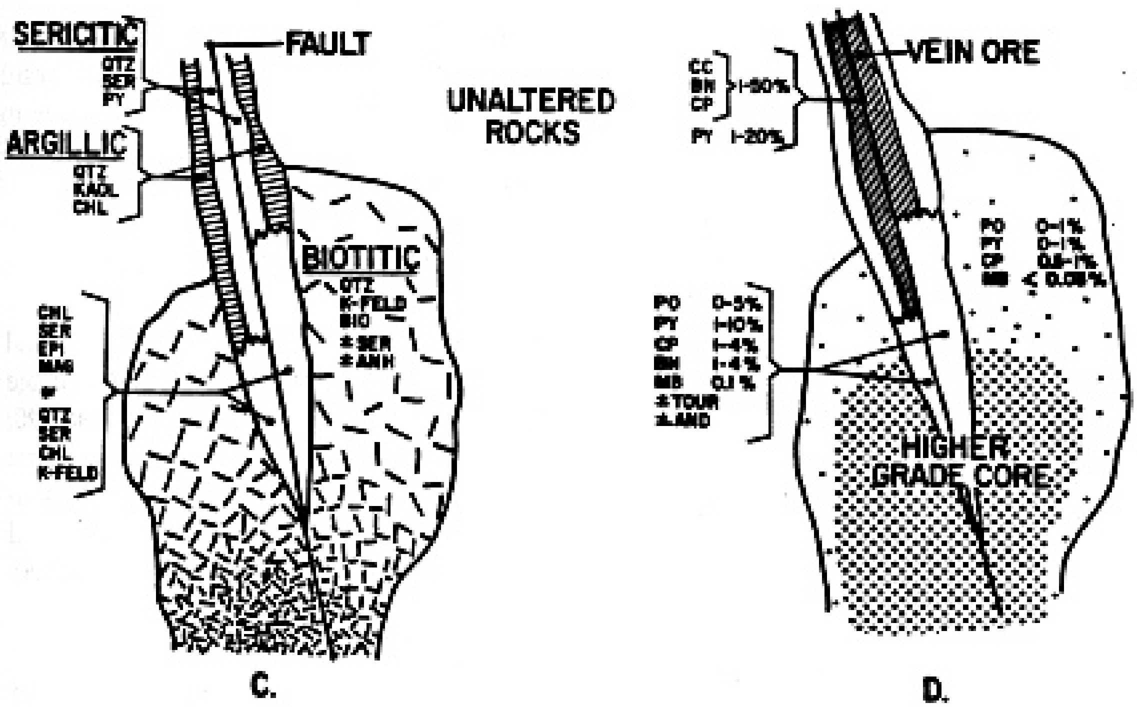
The implication is that Quartz Creek would have to be better than Kalamazoo. Because quartz-dioritic deposits have greater gold contents than quartz monzonitic ones (such as Kalamazoo), the economic viability of Quartz Creek probably depends upon the gold content of any deep copper mineralization.

SUMMARY

Quartz Creek is a presently uneconomic quartz-dioritic, batholithic, copper member of the class of porphyry ore deposits. Although the extent of biotitic alteration exposed at the surface (> 8400 x 2000 x 1460 feet vertically) is impressive, the deposit is likely to remain uneconomic because of the lack of supergene sul-fide enrichment, topography, the depth of any significant tonnage of ore, and the political climate. The very lack of weathering that contributes to the uneconomic nature of Quartz Creek makes it ideal for studying the effects of magmatic and hydrothermal processes.



GUILBERT AND LOWELL MODEL OF PORPHYRY ORE DEPOSITS



BATHOLITHIC ORE DEPOSITS

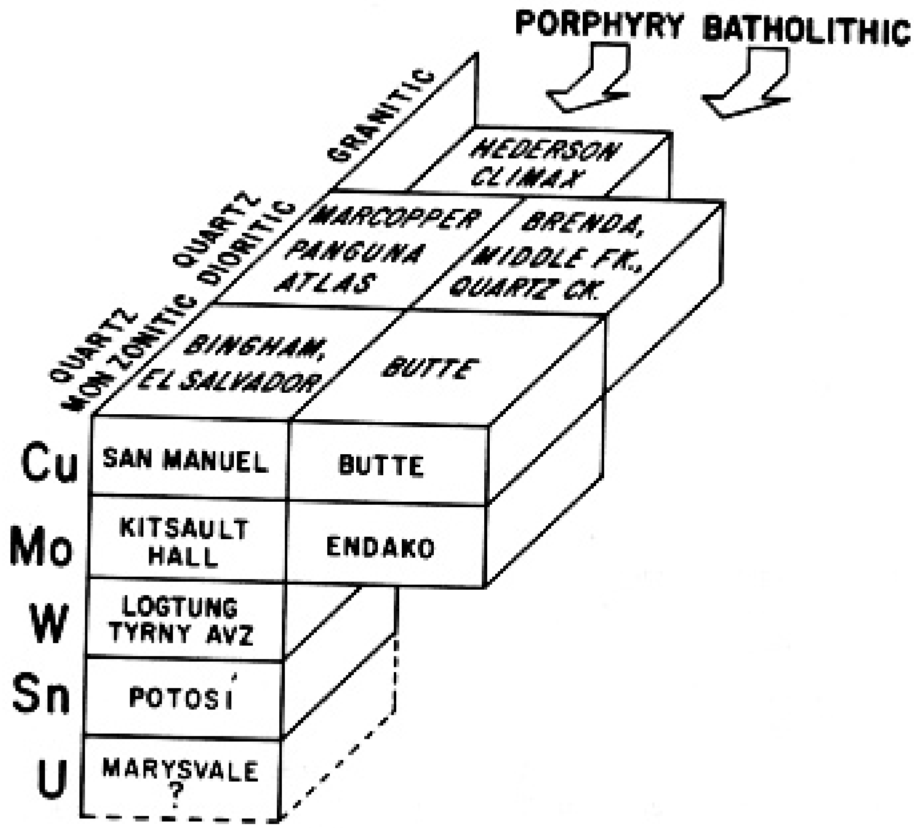


Figure 8 (Above) CLASSIFICATION OF PORPHYRY ORE DEPOSITS

Figure 7. (Left) MODELS FOR PORPHYRITIC AND BATHOLITHIC ORE DEPOSITS

7A and 7B show the concentric zones of alteration and mineralization popularized by Guilbert and Lowell (1974) for porphyry ore deposits in the southwestern United States. Most of these deposits (frontispiece) are centered on small stocks intrusive into feldspathic rocks (Proterozoic metamorphic rocks and granites, Mesozoic arkoses and volcanic rocks, and Tertiary volcanic rocks).

Figures 7C and 7D are modeled after the batholithic ore deposit at Butte, Montana, where quartz-sericitic alteration occurs along faults within and extending above the biotitic alteration (cf. Proffett in Miller, 1973, Roberts in Miller, 1973; Brimhall, 1979, fig. 1). At the Quartz Creek batholithic deposit, quartz-sericite is restricted to breccia pipes. Note that the hydrothermal alteration pattern of batholithic deposits is “inside-out” with respect to the usual porphyry copper deposit of the southwestern U.S.

In both porphyritic and batholithic deposits, quartz-sericitic-pyrite (QSP) alteration is superimposed on biotitic-feldspathic alteration, causing both enrichment of copper grades and the formation of composite alteration assemblages. At Butte, Montana, the biotitically altered rocks contain 96% of the copper in the system at an average grade of 0.4%; whereas, the veins contain 4% of the copper in the system and for many years produced 4% copper.

Much of the argillic alteration in porphyry systems (Fig. 7A) is now known to be associated with weathering.

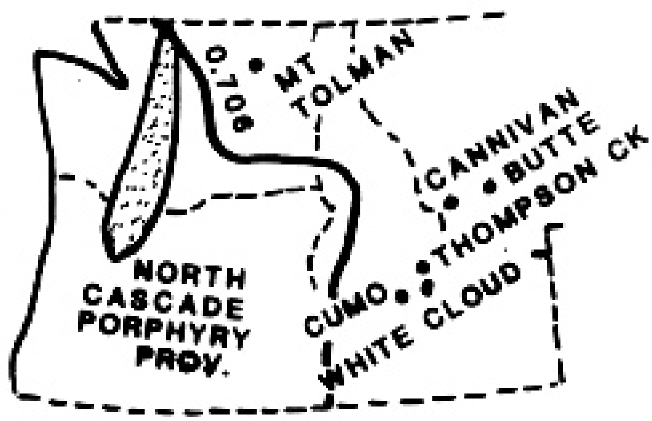


Figure 9. DISTRIBUTION OF PORPHYRY ORE SYSTEMS IN THE PACIFIC NORTHWEST.
Note the initial strontium isotopic line of 0.706 (87Sr/86Srj > 0.706). East of this line the initial composition of Mesozoic plutons is > 0.706, but to the west is generally < 0.704 (Armstrong et al., 1978). Porphyry molybdenum and quartz monzoni tic porphyry copper deposits are east of the line. The North Cascade porphyry ore province is west of the line and is caused by plutons emplaced through accreted terranes.

The North Cascade porphyry province is also coincident with what is commonly (and erroneously) referred to as the "Cascade magmatic arc." The intrusive portion of this province is not arcuate (Fig. 2). More importantly, the Miocene and olderplutons and volcanic rocks of this province are exposed due to the post-2.0 Ma uplift upon which the present Cascade volcanoes are constructed; that is, the Oligo-Miocene plutons are unrelated to the Pleistocene Cascade volcanoes. The eastern margin of the province is largely defined by the unconformably overlying Walpapi sequence (Fig. 1). The western margin of the province is mostly the erosi onal edge of the Kittitas sequence, to the west of which is the older Challis sequence preserved in the Puget Lowland. The southern end of the province is due to the post-2.0 Ma regional dip, which causes Kittitas-aged and older rocks to plunge below the High Cascade sequence.

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