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Arkose-Hosted, Aquifer-Controlled, Epithermal Au-Ag Mineralization, Wenatchee, Washington

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Abstract

The Wenatchee district, site of the Cannon mine, is located on the east flank of the Cascade Range in central Washington. Epithermal gold mineralization of Eocene age (44 Ma) is hosted by the Eocene Chumstick Formation, a sequence of interbedded arkosic sandstone, conglomerate, and mudstone. This study focuses on the structure and hydrothermal alteration and mineralization south of the Cannon mine.

Hydrothermal alteration and mineralization is hosted by Chumstick arkose, minor Eocene dacite, and andesite dikes, and locally, Eocene felsic volcanic rocks (flows, ash flows, eruption breccia) and extends for at least 4 km southeast of the Cannon mine. The district-scale structure is dominated by a postmineralization, northeast-verging fold and thrust belt which consists of three major southwest-dipping reverse faults and associated folds produced by the propagation of the faults.

Arkose-hosted alteration consists of zones of silicification which grade symmetrically outward to argillization and a widely dispersed, district-scale propylitic alteration. Alteration is strata bound within units of arkosic sandstone and conglomerate bound or capped by mudstone-rich sections. Features of the propylitic zone include the growth of pyrite within detrital biotite and the replacement of plagioclase by carbonate and epidote. The argillic assemblage includes hydrothermal kaolinite and sericite. Silicification consists of silicic hydrothermal breccias and pervasive quartz flooding closest to the argillic zone; hydrothermal K feldspar is common. Typically, a transitional subzone containing abundant quartz veins (quartz stockwork) occurs between the argillic and silicic zones.

In decreasing order of abundance, metallic phases are pyrite, arsenopyrite, marcasite, stibnite (latest in paragenesis), chalcopyrite, hessite, electrum, native silver, sphalerite, galena, pyrargyrite, and boulangerite. Gold contents are highest in silicic alteration and the quartz-stockwork subzone. Where arsenic contents are high, gold is concentrated in the argillic zone. In the latter case, strong correlations between gold and arsenic suggest that gold may have been transported as a gold thioarsenide complex; precipitation of the gold and arsenic may have been promoted by the progressive sulfidation of biotite.

Two laterally extensive strata-bound alteration zones (≥2 km along strike) have been delineated, one largely bound by mudstones in the hanging wall of a postmineralization reverse fault, and one in the footwall of the fault and bound above by a mudstone and ash-flow tuff. The absence of alteration stratigraphically above the footwall zone indicates that it is the stratigraphically highest mineralized aquifer in the district. Hydrothermal fluids migrated laterally along at least two laterally extensive aquifers which were stratigraphically stacked. The shallower footwall zone is enriched in As, Sb, and Au relative to the deeper hanging wall zone, which is richer in Ag, Cu, Te, and Se. This variation in depth is similar to patterns observed in active geothermal systems and epithermal precious metal deposits and implies some degree of exchange of hydrothermal fluids between the aquifers, possibly via leaks in aquitards.

Introduction

THE Wenatchee district (Fig. 1) is located on the east flank of the Cascade Range in central Washington and is the site of arkose-hosted gold mineralization of Eocene age. Production from the Lovitt mine, also known as D reef (Fig. 2), from 1949 to 1967 totaled 1,036,572 tons of ore averaging 0.396 oz/ton Au and 0.607 oz/ton Ag (Patton and Cheney, 1971). In 1985, Asamera Minerals (U.S.) Inc. commenced production from the Cannon mine or B reef to the northwest, which contained reserves of 5,256,000 short tons at 0.214 oz/ton Au and 0.5 oz/ton Ag when mining began (Bartholemew, 1986).

Similar epithermal mineralization, consisting of altered and mineralized arkose, extends southeast from the Cannon mine, to the dormant Lovitt mine, and to the subsurface of Wenatchee Heights (Fig. 2). This report focuses on the structure and alteration southeast of the Cannon mine in the area of Wenatchee Heights and describes the district-scale structure, form of mineralization, ore controls, and the nature of the hydrothermal system.

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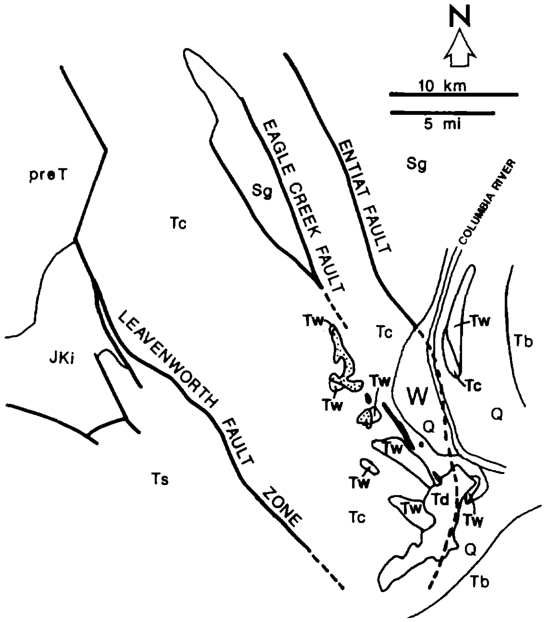


FIG. 1. Generalized geologic map of the Wenatchee region modified from Gresens (1983) and Tabor et al. (1982, 1987). Pre-Tertiary units: JKi, Ingalls tectonic complex; preT, undifferentiated metamorphic and plutonic rocks; Sg, Swakane Biotite Gneiss. Q, Quaternary Tertiary units: Tb, Columbia River Basalt; Tc, Chumstick Formation; Td, Pliocene diamictite; Ts, Swauk Formation; Tw, Wenatchee Formation. Tertiary intrusive rocks: solid black, Eocene; stippled, Oligocene. W = city of Wenatchee.

Geologic Setting

Wenatchee lies within the Chiwaukum graben, a strike-slip basin defined by the Entiat fault zone to the east and the Leavenworth fault zone to the west (Fig. 1; Gresens, 1983; Johnson, 1985; Evans, 1988). Although Quaternary deposits obscure the position of the Entiat fault south of the city of Wenatchee, the fault may curve to the southwest beneath Wenatchee Heights where it is informally called the Wenatchee Heights fault zone (Margolis, 1987; Figs. 1 and 2). The Entiat fault system was apparently active before, during, and after deposition of Chumstick sediments within the graben (Laravie, 1976; Vance, 1985; Evans, 1988). There is no evidence of intrusive or hydrothermal activity southeast of the trace of the Wenatchee Heights fault zone.

The area between the Entiat and Leavenworth faults consists of the Chumstick Formation of Middle-to-Late Eocene age, a basin-fill sequence of continental arkosic sandstone with interbedded mudstone, siltstone, and conglomerate. Interbedded tuffs yield ages between 49 and 41 Ma, although the top of the formation may be close to the Eocene-Oligocene boundary (Tabor et al., 1982; Evans, 1988). The Chumstick Formation hosts the Wenatchee epithermal mineralization (Margolis, 1987). The Eagle Creek fault (Fig. 1) was active during Chumstick deposition (Evans, 1987). Near Wenatchee, pre- and postmineralization Eocene intrusions are restricted to a narrow, northwest-trending zone on strike with the Eagle Creek fault (Fig. 1). It is inferred that this basement fault provided ingress for magma during basin formation. Premineralization dikes and stocks range from basaltic andesite, possibly of alkalic affinity, to hornblende andesite and dacite and are variably altered (Gresens, 1983; Margolis, 1987).

Mineralization at the Cannon mine has been dated at 44 Ma (K-Ar on adularia; Ott et al., 1986). Porphyritic rhyolite of the Wenatchee dome, adjacent to the Cannon mine, is interpreted as a postmineralization intrusion based on its lack of alteration and K-Ar age of 43 Ma (Gresens, 1983; Ott et al., 1986).

The Chumstick Formation was regionally folded prior to the deposition of the Wenatchee Formation of Oligocene age (34 Ma; fission track; zircon in tuffaceous bed; Gresens et al., 1981). The Wenatchee Formation unconformably overlies the Chumstick Formation and older rocks and consists of at least 300 m of quartzose sandstone, shale, and minor tuffaceous beds (Hauptman, 1983). Dikes and sills of hornblende andesite, dated at 29 Ma (K-Ar on hornblende; Gresens, 1983), intrude both the Wenatchee and Chumstick Formations.

Geology of Wenatchee Heights

Norco volcanic complex

Much of the area south of the Cannon mine is covered by basaltic diamictite of Pliocene age and unconsolidated deposits of Quaternary age (Fig. 2). A section of altered felsic volcanic rocks of Eocene age, informally termed the Norco volcanic complex, underlies diamictite in the vicinity of the Norco well, a wildcat well drilled for natural gas in the 1930s (Fig. 2). All information on the Norco volcanic complex is from examination of 12,000 ft of drill core from six drill holes. The Norco volcanic complex consists of a basal section of porphyritic rhyodacite flows and flow breccias. The flows are overlain by more silicic, strongly welded rhyolite ash-flow tuffs and interbedded, discontinuous horizons of bedded breccias, as much as 60 m thick, which may be hydrothermal explosion deposits (Margolis, 1987). A K-Ar age of 47.3 ± 1.8 was obtained from biotite in a relatively unaltered rhyodacite flow at the base of the section. The volcanic rocks vary in thickness from 100 to 200 m; their complete areal extent has not been delineated. Similar lithologies have not been found elsewhere in the Chiwaukum graben, although thin air-fall and ash-flow tuffs are present in the Chumstick Formation (Gresens et al., 1981; McClincey, 1986). Norco volcanic complex volcanism predates mineralization because both the Norco volcanic complex and at least

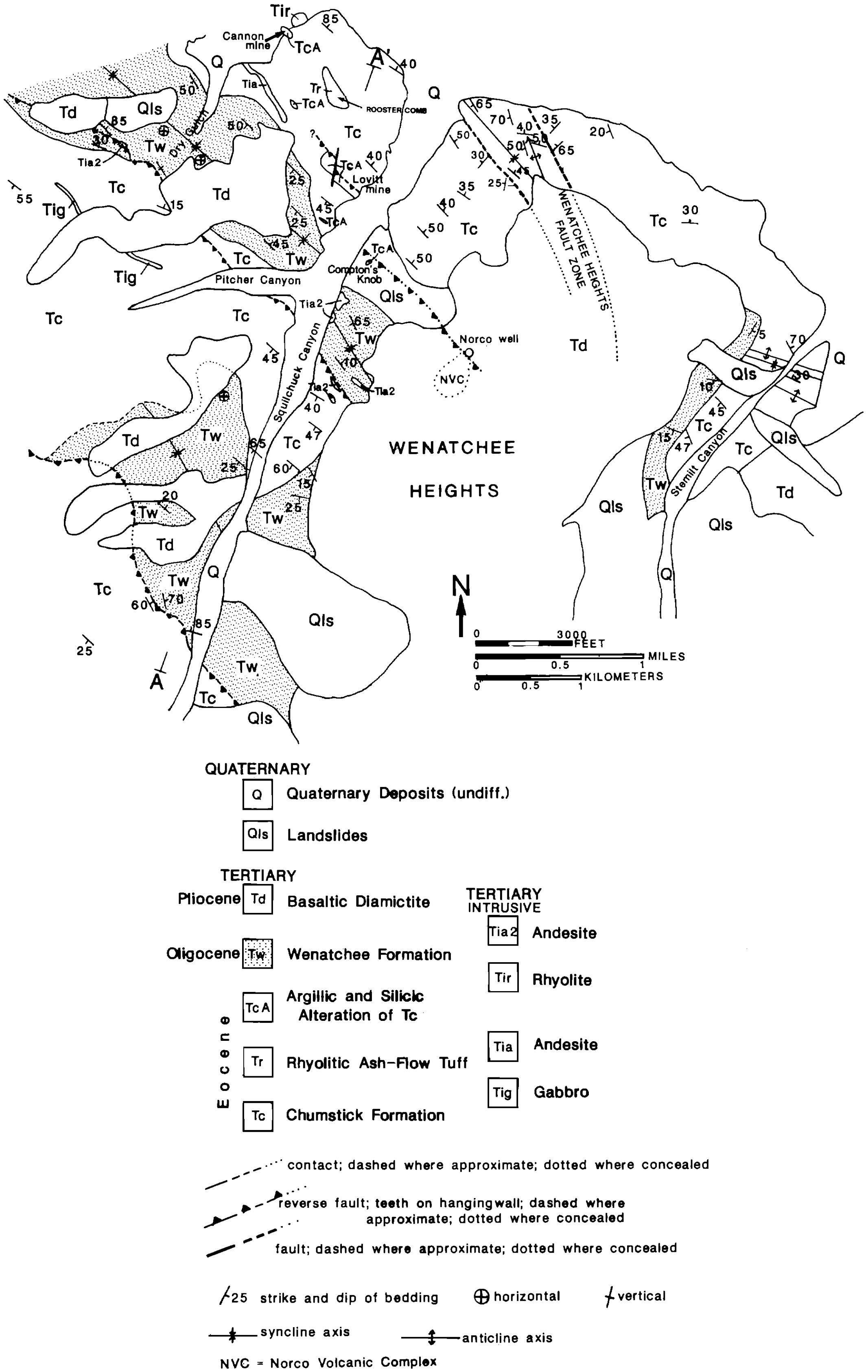


FIG. 2. Geologic map of Wenatchee Heights modified from Gresens (1980, 1983) showing the locations of the Cannon mine, Lovitt mine, Compton's Knob, and known extent of the Norco volcanic complex. The city of Wenatchee is located immediately north of the Cannon mine.

100 m of overlying arkose are weakly altered and mineralized.

Compton tuff

A strongly welded, felsic ash-flow tuff, about 30 m thick, has been delineated by drilling and mapping from the area of the Norco well northwest to the rhyolite exposed at Rooster Comb, several hundred meters northeast of the Lovitt mine (Fig. 2). This unit, informally named the Compton tuff by Margolis (1987), contains quartz, biotite, and oligoclase phenocrysts, is partially perlitic, and has been dated at 46.2 ± 1.8 Ma (K-Ar, biotite). The similarity in phenocryst assemblage between this tuff and the Norco volcanic complex tuffs, the proximity of the tuff to the Norco volcanic complex, and its age suggest that it may be an outflow sheet from the Norco volcanic complex.

Structural Geology

The district-scale structure is dominated by a postmineralization, post-Wenatchee-age, northeast-verging fold and thrust belt. The belt is at least 6 km wide by 15 km along strike and consists of three major southwest-dipping reverse faults and associated folds produced by the propagation of the faults (Fig. 3). Gresens (1983) recognized that andesite which intruded the plane of the Dry Gulch fault is part of the Oligocene intrusive complex (29 Ma) and constrains the time of deformation to between 29 and 34 Ma, the age of the Wenatchee Formation. The footwall fissure reverse fault in the Lovitt mine and the Dry Gulch reverse fault were recognized previously (Lovitt and Skerl, 1958; Gresens, 1983), but the relationship of the faults to mineralization and folds was not resolved. The fold and thrust pattern was superimposed upon a regional anticlinorium in the Chumstick Formation which developed prior to deposition of the Wenatchee Formation. The axis of this anticlinorium coincides with the easternmost reverse fault (Fig. 3), and the southwest-dipping, generally bedding-parallel reverse faults failed to propagate in the northeast-dipping limb of the anticlinorium.

In the area of exposed and near-surface mineralization south of the Cannon mine, the structure consists of a fault-propagation fold (Lovitt anticline) cored by the footwall fissure reverse fault (Figs. 3 and 4). The term "footwall fissure" was first used because the fault marks the footwall to the D reef mineralization at the Lovitt mine (Lovitt and Skerl, 1958). Both the work of Patton (1967) within the mine and data from more recent drilling show that the fault is listric and dips southwest, and that drag folding exposed in the footwall northeast of the fault indicates reverse movement (Fig. 4). Right-lateral, nearly north-striking faults offset the D reef and the footwall fissure by as much as 100 m (Lovitt and Skerl, 1958; Patton, 1967) and offset alteration patterns (Margolis, 1987). The

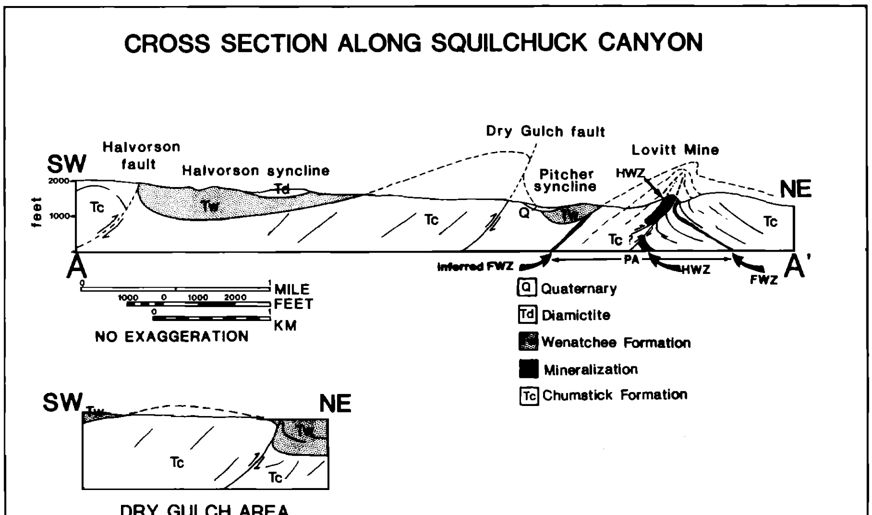


FIG. 3. Geologic cross section A–A′ along Squilchuck Canyon; see Figure 2 for location of section line. The section illustrates the postmineralization fold and thrust pattern, the fault-propagation fold (Lovitt anticline) at the Lovitt mine cored by the footwall fissure, and the unconformable relationship between Tc and Tw. Also note the pre-Tw anticlinorium in Tc, and the axis of this fold at the Lovitt mine. HWZ = hanging-wall zone, FWZ = footwall zone, PA = propylitic alteration. Cross section at lower left is along Dry Gulch, one mile northwest of section A–A′.

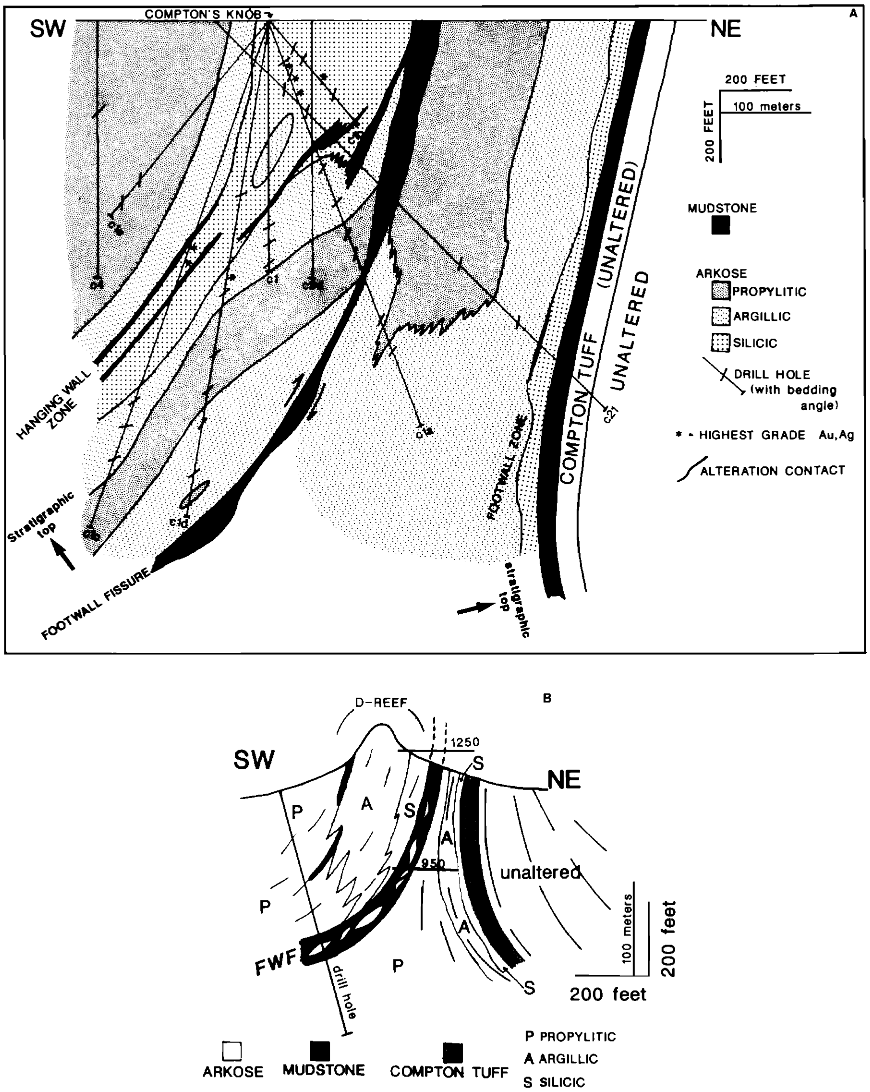


FIG. 4. A. Cross section oriented southwest–northeast through Compton's Knob southeast of Squilchuck Creek showing the generally strata-bound nature of alteration, the position of the hanging-wall and footwall zones, and the absence of alteration stratigraphically above the Compton tuff. Note that the footwall zone is overturned by drag folding along the footwall fissure fault. B. Cross section through the Lovitt mine on the northwest side of Squilchuck Creek. (FWF = footwall fissure). D reef is the hanging-wall zone, the footwall zone is the silicic and argillic alteration beneath the Compton tuff. Note the drag folding (steepened to overturned bedding) in the footwall to the footwall fissure and the absence of alteration above the tuff.

angle between the footwall fissure and the right-lateral faults is about 30°, suggesting that the right-lateral faults are tear faults which were active during the northeast compression that caused the reverse faulting.

The footwall fissure at the D reef is marked by a mudstone-rich section which, due to its incompetence with respect to adjacent altered arkose, preferentially accommodated bedding-parallel deformation. The mudstone-rich section is as much as 15 m thick and characterized by a slickensided, anastamosing scaley fabric; thinner beds of unaltered arkosic sandstone within the mudstone are disrupted and boudinaged. The footwall fissure is a narrow zone of discontinuous, en echelon faults accommodated by discontinuous mudstones. At the northwest margin of the D reef, a similar section of variably deformed mudstone marks the hanging wall of the mineralized arkose; the mineralization is, therefore, generally strata bound (Fig. 4). Ott et al. (1986) showed that mineralization in the Cannon mine is similarly confined between mudstone-rich sections.

Form of mineralized zones

From the area of Rooster Comb southeast through the area of Compton's Knob (Fig. 2), two tabular zones of mineralization, generally parallel to bedding, have been delineated (Figs. 3 and 4). One zone, the hanging-wall zone, occurs in the hanging wall to the footwall fissure; the second zone, the footwall zone, occurs in the footwall of the fault (Fig. 4). The hanging-wall zone includes the D reef of the Lovitt mine and alteration at and subjacent to Compton's Knob (Fig. 4).

The footwall zone is concealed by landslide deposits southeast of Squilchuck Canyon and only poorly exposed northwest of the canyon at the Lovitt mine. The zone lies east of Compton's Knob and the D reef and consists of silicified sandstone and conglomerate stratigraphically below a laterally continuous mudstone which underlies the Compton tuff. On the northeast limb of the Lovitt anticline, the footwall zone dips northeast about 35° to 45°, but because of postmineralization drag folding by the footwall fissure reverse fault, the section is steep to overturned adjacent to the fault (Figs. 3 and 4). Throughout the district, alteration occurs only stratigraphically below the mudstone and Compton tuff. If this zone is laterally extensive, it should occur on the southwest limb of the Lovitt anticline beneath the Wenatchee Formation (Fig. 3).

Hydrothermal Alteration

Hydrothermal alteration consists of tabular zones of silicification which grade symmetrically outward to zones of argillization and widely dispersed propylitization. Figure 5 illustrates the principal mineralogic changes. Alteration contacts within arkose are gradational, but commonly, carbonaceous mudstones and siltstones sharply separate alteration types. The description of alteration given below pertains to arkose, the dominant lithology.

Unaltered Chumstick arkose contains quartz (40%), plagioclase (40%), orthoclase-microcline (10%), biotite (5%), fragments of volcanic, plutonic, and metamorphic rocks, and minor accessory minerals. Detrital biotite is black in hand specimens, unaltered, and locally constitutes as much as 20 percent of the arkose.

Propylitic alteration

The most conspicuous feature of propylitic alteration is the occurrence of pyrite within grains of detrital biotite (Fig. 6A) which are distinctly bronze in hand specimens, unlike the black unaltered biotite. Nearly all sulfide in the propylitic zone occurs as pyrite in altered biotite grains; the pyrite is typically parallel to biotite (001) cleavage. The district-wide, propylitized Chumstick arkose had been previously interpreted as a different formation by Gresens (1983).

Argillic alteration

The alteration is termed argillic because of the presence of kaolinite. Sulfides are most abundant in the argillic zone, occurring as stringers or disseminations, the latter chiefly within former biotite sites. Adjacent to the silicic zone, sulfide veinlets are cut by multiple generations of quartz veins and the arkose

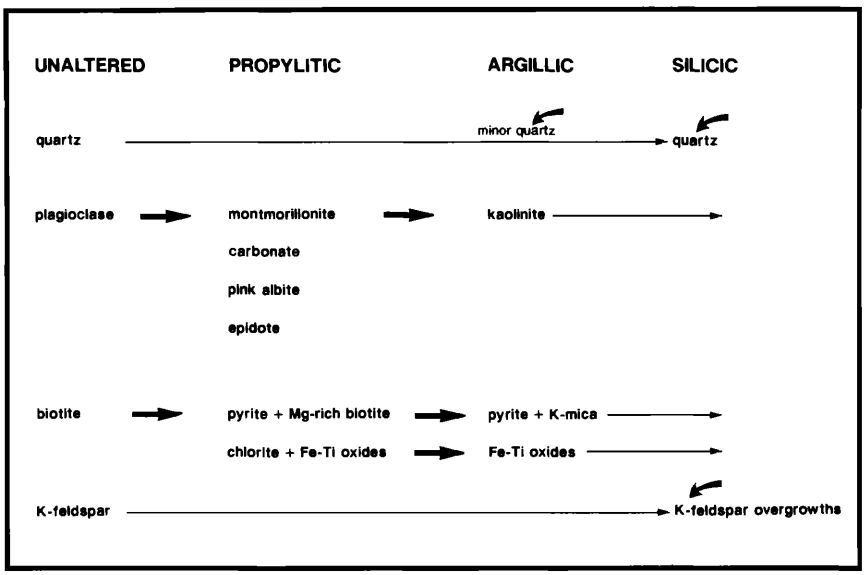


FIG. 5. Diagram illustrating the principal mineralogic changes resulting from alteration of arkose. Curved arrows indicate addition of quartz and K feldspar. Light arrows indicate stability, heavy arrows indicate reactions.

is more completely silicified. This is the quartz stockwork subzone (Fig. 6F). The quartz veins are rarely greater than 3 cm wide, with notable exceptions in the D reef, where veins are as wide as 1 m. Fracturing of the arkose and concomitant vein emplacement could occur only after initial periods of argillic and silicic alteration, which served to create a more brittle host through the deposition of hydrothermal quartz in the matrix.

Silicic alteration

Two types of silicification are present at Wenatchee Heights: silicic breccias and quartz flooding adjacent to the argillic zone. In general, silicic breccias grade symmetrically into a zone of quartz flooding which in turn grades into the argillic zone with an intervening quartz stockwork.

Silicic breccias are characterized by angular, silicified clasts in a siliceous rock-flour matrix which typically contains carbonate. In areas of quartz flooding the clastic texture of the arkose is preserved, and most sulfide is confined to the altered arkose with only minor sulfide occurring in quartz veins. The quartz veins are most common in the quartz-stockwork subzone at the transition from argillic to silicic alteration.

In the silicic zone detrital K feldspar is largely preserved, and many of the grains have overgrowths of secondary K feldspar (Fig. 6B). Apparently, preexisting K feldspar grains served as a nucleus for the precipitation of hydrothermal K feldspar.

Geochemistry and sulfide mineralogy

Figure 7 illustrates the distribution of sulfides in alteration zones. Except for pyrite (<2 mm) and stibnite (<1 cm), the sulfide grains rarely exceed 0.5 mm in diameter. The Au and Ag contents increase from the propylitic to the silicic zone. Where present, the quartz stockwork subzone is richest in Au and Ag, which occur as electrum and sulfides within the quartz veins. Outside of the quartz stockwork subzone, Au contents are higher in argillic alteration in the footwall zone and in silicic alteration in the hanging-wall zone.

Reports on the mineralogy of the D reef (Moody, 1958; J. M. Guilbert, 1963, unpublished report for Day Mines, Inc.) indicate that it is similar to mineralization at Compton's Knob in that both contain abundant hessite, electrum, chalcopyrite, and apparently no arsenopyrite. Guilbert (1963) reported naumannite from the D reef although in this study no Se phase was detected. Guilbert's finding does, however, indicate that Se contents are at least locally high in the hanging-wall zone.

Significant mineralogic differences between the footwall and hanging-wall zones are summarized in Figure 7. Geochemically, the hanging-wall zone is richer in Ag, Te, Cu, and Se than the footwall zone, which is richer in As, Sb, and possibly Au.

In the argillically altered rocks of the footwall zone, there is a strong positive correlation between As and Au (Fig. 8). Although the Au:As ratio varies among different drill-core intervals, within each interval the ratio is uniform. There is no systematic pattern of As and Au concentration as a function of depth or location along strike.

Discussion

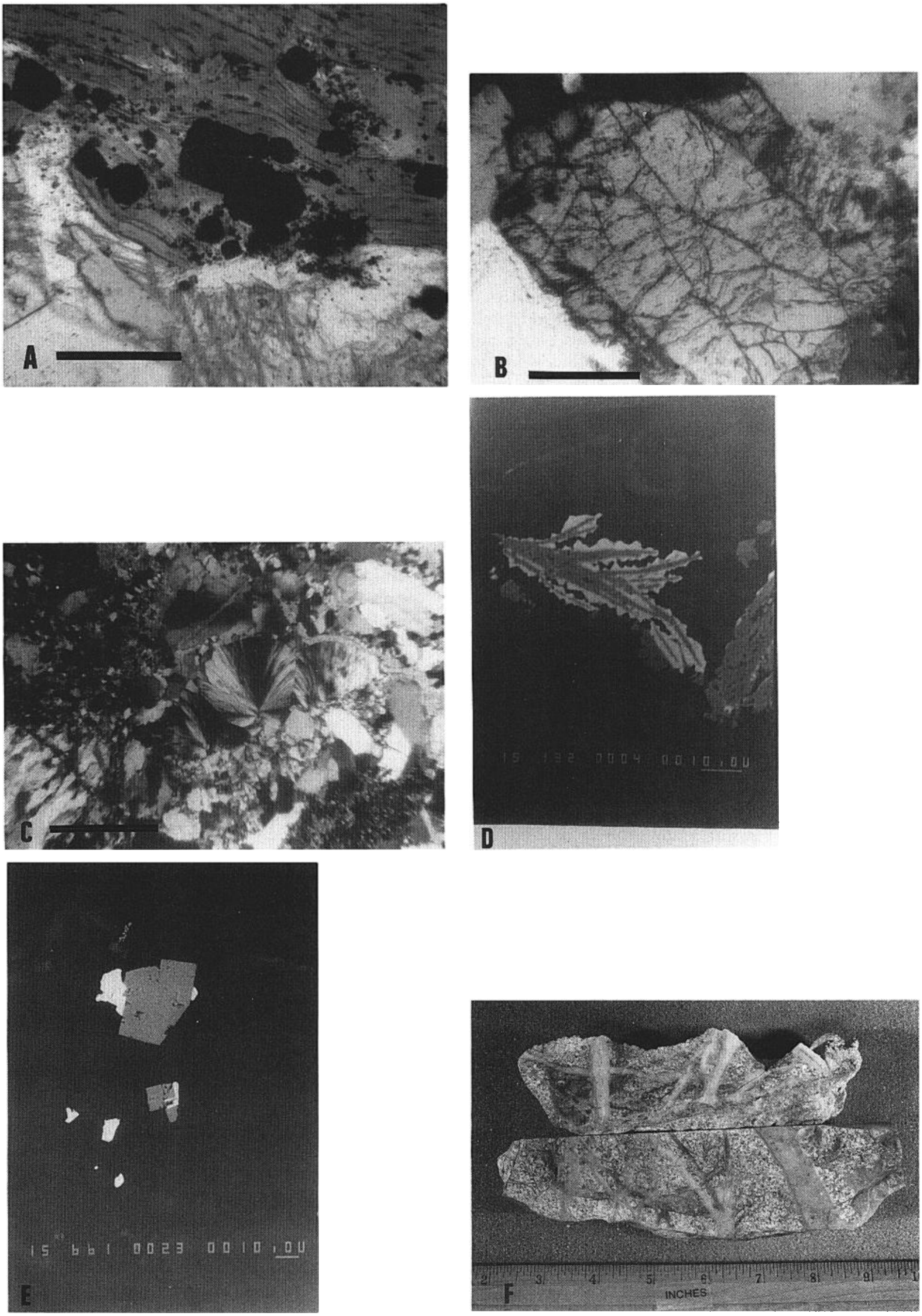
Hydrothermal aquifers

When mineralization took place at 44 Ma, the Chumstick Formation was still being deposited and the section must have lain nearly flat. Premineralization folds in the Cannon mine (Ott et al., 1986) may reflect local deformation related to the inferred subjacent Eagle Creek fault and/or to intrusive activity. Early workers such as Lovitt and Skerl (1958) stressed the importance of large structures such as the footwall fissure in focusing mineralizing fluids. However, these structures clearly postdate mineralization. Most recently, Ott et al. (1986) recognized the importance of permeability and the generally strata-bound form of the alteration in the Cannon mine.

Throughout the district it is apparent from the strata-bound distribution of the alteration that hydrothermal fluids migrated laterally along aquifers of sandstone and conglomerate at least partially confined between or capped by mudstones (Fig. 9). Some of the resulting mineralized zones (aquifers) are at least 2 km long (along strike) but others such as the E reef, several hundred meters southwest of the D reef, are relatively discontinuous. The unsilicified mudstones bounding the silicified sandstone aquifers preferentially accommodated bedding-parallel slip during later Oligocene deformation. Although this study is concerned with the area south of the Cannon mine, the steeply dipping and deformed mudstones bounding the isolated orebodies in the Cannon mine (Morrow and Follis, 1988) may represent the northwest extension of the footwall fissure fault zone.

The absence of alteration stratigraphically above the Compton tuff indicates that the alteration zone immediately beneath it (footwall zone) represents the stratigraphically highest mineralized aquifer in the district and that it is stratigraphically above the hanging-wall zone. Thus the mineralized aquifers were stacked.

There are geochemical differences that resulted from this stratigraphic stacking. The shallower footwall zone is enriched in As, Sb, and Au, compared with the deeper hanging-wall zone which is richer in Ag, Cu, Te, and Se. This variation in geochemistry is similar to patterns observed in active geothermal systems and many epithermal precious metal deposits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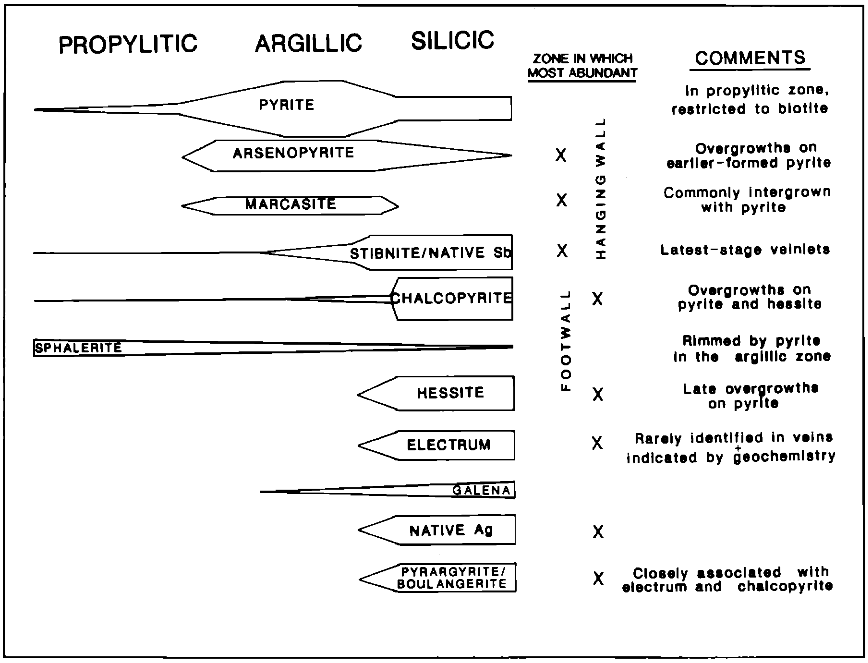

FIG. 7. Distribution of sulfides, native metals, and tellurides within the silicic, argillic, and propylitic zones south of the Cannon mine. Also shown is the strata-bound zone in which each mineral is most abundant. Identification of these minerals was by electron microprobe.

(Ewers and Keays, 1977; Buchanan, 1981; White, 1981). Assuming that mineralization in the aquifers was coeval, such a distribution implies some degree of exchange and interaction of hydrothermal fluids between the major aquifers, possibly via leaks in aquitards as shown in Figure 9.

The depth from the paleosurface to the Compton tuff at the time of mineralization is not known. Based on the structure and distribution of propylitic alteration (Fig. 3), the stratigraphic distance between the two major aquifers south of the Cannon mine is about 300 m. The lateral flow within aquifers and the damming by the mudstone and Compton tuff probably prohibited the discharge of solutions at the surface, at least in the area that has been studied. Furthermore, it is unlikely that pervasive fractures were present to channel solutions in the poorly consolidated arkose.

One problem that remains unsolved is the direction of fluid flow, which may be addressed by district-scale studies of mineralogic, isotopic, and fluid inclusion-temperature zoning. The lateral extent (perpendicular to strike) of mineralized aquifers is also unknown. A third unresolved problem is the position of the Cannon mine ore zones with respect to the two major mineralized aquifers to the south.

Alteration paragenesis

Textures of alteration minerals and sulfides (Fig. 6D, E, and F) indicate that the alteration zones have encroached upon one another toward unaltered ar-

FIG. 6. A. Photomicrograph of pyrite grains (opaque) within Mg-rich biotite (top) in the propylitic zone; sample C9-602; scale bar is 250 μm. B. Photomicrograph of a detrital K feldspar grain with a rim of hydrothermal K feldspar; silicic hanging-wall zone, sample C9-192. Scale bar is 250 μm. C. Three coalesced spherical growths of chalcedony (center) in a quartz vein; silicic footwall zone, sample C12-592. Chalcedony fibers display negative elongation; scale bar is 250 μm. D. Backscattered electron image of elongate pyrite (gray) within altered biotite rimmed by arsenopyrite (white); argillic footwall zone, sample C5-1278. Photo illustrates the overprinting of argillic alteration on earlier formed propylitic alteration represented by the elongate pyrite in biotite. E. Backscattered electron image of euhedral pyrite (gray) rimmed and partially replaced by hessite (white); silicic hanging-wall zone, sample C1C-750. Photo illustrates overprinting of Ag-Te-rich silicic alteration on earlier formed argillic pyrite-rich zone. F. Two core samples of the quartz stockwork subzone representing the transition from argillic to silicic alteration in arkose. Photo illustrates the abundant quartz veins (gray) cutting previously formed stringers of sulfide (dark gray) which formed during argillic alteration. Samples jrd3-1343, C1C-1124.

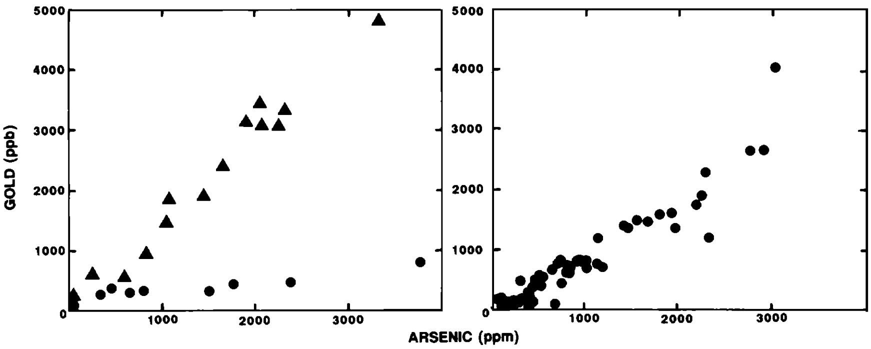

FIG. 8. Plots illustrating the strong correlation between arsenic and gold in two drill holes east of Squilchuck Creek. Circles = altered arkose, triangles = altered felsite. Left figure is from footwall zone near Compton's Knob (hole C-16); right figure is from argillized arkose overlying the Norco volcanic complex (hole jrd-3). Altered felsite is not the Compton tuff, but possibly a thinner ash-flow tuff (?) or a rhyolite dike. In all cases where data are available, argillized felsite of the Norco volcanic complex has a higher Au:As ratio than associated arkose. Analyses on five-foot intervals by instrumental neutron activation analysis (INAA) by Bondar-Clegg and Co., Ltd., Vancouver, B. C.

kose—silicic alteration has overprinted argillically altered arkose, and argillic alteration has overprinted propylitically altered arkose. The best evidence for this is that elongate pyrite of the propylitic zone, which formed within biotite, is progressively replaced and rimmed by arsenopyrite in the argillic zone (Fig. 6D). In addition, sulfide veinlets of the argillic zone are cut by a quartz stockwork at the edge of the silicic zone (Fig. 6F), and veinlets of kaolinite commonly cut propylitic alteration. Veinlets of euhedral stibnite and minor native antimony, commonly within calcite, represent the final stage of sulfide mineralization. The late precipitation of stibnite and native antimony may have been promoted by decreasing activity of sulfur with time (Barton and Skinner, 1979).

Precipitation mechanisms

Conclusions concerning precipitation mechanisms are more preliminary and speculative than conclusions reached above concerning the nature of the hydro-

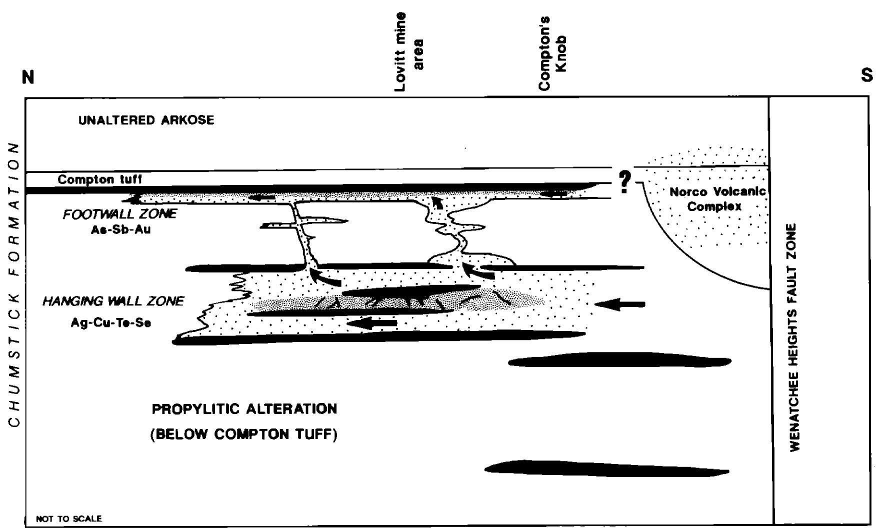

FIG. 9. Schematic representation of the district-scale hydrothermal system discussed in the text. Note the dominantly lateral fluid flow (arrows), leaks in aquitards, the stratigraphically stacked position of the precious metal-rich footwall zone and the base metal-rich hanging-wall zone, and the distribution of alteration. A northerly direction of fluid flow is shown for the purpose of illustration, but the actual direction of flow is not known. Black = mudstone, open stipple = argillic alteration, dense stipple = silicic alteration, lines = veins. The relationship between alteration at the Norco volcanic complex and the aquifers to the north is not known; nor is the relationship between the Cannon mine ore zones and the two major aquifers.

thermal system and the alteration paragenesis. It is hoped that these ideas guide future research efforts.

Boiling: Comb-structured quartz veins in zones of silicic alteration commonly contain centers of finer grained anhedral quartz or are cut by veins of similar material. Chalcedonic spheres (Fig. 6C) are also common in the latest veins of anhedral quartz. These features may have resulted from silica supersaturation during rapid decompressional boiling, which would cause the precipitation of chalcedony and amorphous silica gel, now anhedral quartz and spherical chalcedony, respectively (Fournier, 1985). Other possible features derived from boiling such as calcite-cemented breccias are outlined by Margolis (1987); all are late in the paragenesis within the silicic zone. It is likely that initial silicification formed impermeable areas which led to increased hydrothermal fluid pressure. Sudden rupturing would then result in decompressional boiling (Fournier, 1985; Hedenquist and Henley, 1985) and the emplacement of boiling fluids into the resulting fractures and breccias. Fluid-inclusion studies at the Cannon mine indicate that hydrothermal fluids boiled (Klisch, 1989).

Gold thioarsenide complexing: The correlations between Au and As (Fig. 8) in the argillic alteration of the footwall zone suggest that gold thioarsenide complexing occurred (cf. Seward, 1984) and that the arsenopyrite may be auriferous. Preliminary microprobe studies, however, failed to detect Au in the arsenopyrite. In the hanging-wall zone at Compton's Knob, As contents are lower, arsenopyrite is rare, and gold precipitated as electrum in the silicic zone.

Sulfidation of biotite: Petrographically, it is clear that iron for the abundant pyrite was provided by detrital biotite in the arkose. Influx of sulfur-bearing solutions reacted with iron in black detrital biotite to produce pyrite and secondary Mg-rich bronze biotite. This sulfidation of biotite began in the zone of propylitic alteration (Fig. 6A) and continued in the zone of argillic alteration where biotite is completely altered to sericite and pyrite. This process may have destabilized Au and As sulfide complexes and promoted the simultaneous precipitation of Au and As within argillic alteration of the footwall zone. Although gold was not precipitated during initial sulfidation in the propylitic zone, precipitation of Au and As would occur after a certain degree of sulfur fixation; and this was apparently attained during argillic alteration. The concept of iron-rich phases as favorable reactive sites for sulfide and gold precipitation in environments of sulfide complexing has received increasing attention (Phillips et al., 1984; Neall and Phillips, 1987; Mountain and Wood, 1988; Lhotka and Nesbitt, 1989).

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