UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geology and geochemistry of the Sleeper Gold-Silver Deposit, Humboldt County, Nevada--an interim report

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ABSTRACT

Epithermal gold-silver deposits of the quartz-adularia type at the Sleeper mine were emplaced in a local Miocene rhyolite dome-flow complex south of the McDermitt Volcanic field. The rich deposit is a combination of superimposed very high grade bonanza veins, medium grade breccias, and lower grade stockworks. High-grade banded veins comprise more than 60 percent of reserves, but zones with less than 0.1 ounces per ton (oz/ton) gold also are significant and probably would constitute ore elsewhere without the veins. Silicified rhyolite porphyry is the chief ore host, and local fault blocks of 15.6-Ma welded tuff from the McDermitt Volcanic field host some ore. Altered Tertiary volcanic rocks are exposed on a pediment east of the pits, but the Sleeper orebody is covered by 20-50 m of alluvium.

Structural controls of many types and scales are important at Sleeper. The local volcanic complex and veins reflect late Miocene extensional tectonic activity. Multiple stages of silicification and gold-silver mineralization, and the continuity of vein structures suggest repeated opening of a controlling north-striking fracture zone. A series of steplike Basin and Range faults downdropped the Sleeper deposit about 300-600 m and preserved it from erosion. The main high-grade veins, other ore structures, and Basin and Range faults are cut by north-, northeast-, and northwest-striking high angle-faults having offsets of less than about 15 m that do not greatly complicate mining. Some post-ore structures were the sites of acid leaching and opal-kaolinite-alunite deposition dated at 6 Ma.

Multiple high-grade, banded quartz-adularia-gold veins are semicontinuous for more than 1,200 m along strike and more than 500 m down dip, and are comparable to classic epithermal veins rather than hot springs deposits. In detail, the veins range up to 3 m wide and generally dip 60°-70° W.; commonly the high grade zones comprise many parallel and splaying veins spanning more than 30 m. The veins contain more gold than silver. Locally, gold content averages more than 20 oz/ton, and ranges to more than 170 oz/ton. The paragenesis is consistent over a broad area: formation of spectacular banded electrum and microcrystalline quartz-adularia was followed by brecciation and then by later stages of opal and micro-quartz rich in naumannite or stibnite.

Broad zones of hydrothermal breccias and stockwork veinlets are richer in pyrite and in silver (Ag>Au) than the veins; most of these ore-bearing structures formed after the bonanza veins. Widespread early flooding by silica and pyrite created brittle rocks that were favored for later ore stages. The breccias are clast supported, derived from adjacent wallrocks, and cemented by silica and 5-10 percent pyrite and marcasite. Stockwork veinlet zones grade into the breccias and have similar mineralogy but reflect less dilation.

Alteration of host rocks is broadly controlled by structure but has diffuse boundaries; no reaction selvages are observed along veins or veinlets. Multiple stages of opal, cristobalite, and microcrystalline quartz with fine-grained pyrite, marcasite, and adularia or sericite characterize the ore zone. Igneous textures generally survive except in zones of late acid leaching. Plagioclase phenocrysts have been variably replaced by opal or quartz, sericite, or alunite-kaolinite, but sanidine is little altered. Glassy groundmass perists locally in rocks more than 300 m from ore, but generally has been transformed to aphanitic mixtures dominated by opal. Least altered rocks contain smectite, are sparsely fractured, and contain no ore. Sericite-pyrite alteration is most abundant in lower-grade zones adjacent to veins. All rocks in the pits are enriched in K and S, and depleted in Ca and Na; Al

commonly is mobile. The ore zones are generally enriched in As and Se and are sporadically enriched in Sb, Hg, Tl, and Mo; concentrations of Ba, Bi, Cu, Pb, Te, and Zn are generally low.

The Sleeper gold deposit has most of the features of the quartz-adularia class of epithermal silver-gold deposits hosted by volcanic rocks, but several features suggest that the Sleeper deposit did not form by conventional hydrothermal mechanisms. The abundance of opaline silica, repeated mono- or bi-mineralic layers, and the mass of gold in ore shoots cannot easily be explained by equilibrium thermodynamic models. We suspect that silica and gold were transported and deposited as colloids. Alteration of volcanic glass, supplemented by boiling, may have created very high Si-Au concentrations in ore fluids. Fine banding in veins suggests quiescent, gently effervescent conditions in contrast to adjacent pre- and post-vein hydrothermal breccias. The changes from high sulfide content in breccias to no sulfide in veins may be a reflection of boiling, loss of H_2S, and oxidation.

INTRODUCTION

The high grade and wide distribution of the epithermal gold-silver deposit at the Sleeper mine, Humboldt County, Nevada, make it amenable to low-cost mining and milling operations. The deposit has most of the features of the adularia or adularia/sericite class of epithermal precious metal deposits hosted by volcanic host rocks (Hayba and others, 1985; Silberman and Berger, 1985; Bonham, 1988). We do not use the term "hot springs deposit" because ores at Sleeper span more than 500 m vertically. New geologic information from mine exposures and closely-spaced drill holes clarifies the setting of this rich deposit. Geologic explanations for most features observed at Sleeper are emerging, but details of genetic mechanisms remain enigmatic and require additional knowledge gained by mining and specialized laboratory studies. The geologic ingredients in the formation of this deposit are not so rare that explorationists should discount possibilities for discovery elsewhere.

The Sleeper deposit and mine complex are located in Desert Valley at the base of the Slumbering Hills, Humboldt County, Nevada, about 45 km northwest of Winnemucca (fig. 1). The mine started in 1986 with one open pit, the Sleeper, and in 1987 the Wood pit was excavated a short distance to the south. In 1989 the two pits were joined to make one pit more than 2.4 km long and 0.5 km wide, but the earlier names are retained: Sleeper for the northern part and Wood for the southern. The milling rate was initially about 500 tons per day but was expanded in 1989 to 1,500 tons per day at an average head grade of 0.48 oz/ton (ounces per ton) gold. An additional 17,000 tons per day are crushed and stacked for heap leaching. The cash production cost in 1988 was $103 per ounce of gold (AMAX Gold, 1989). Production from 1986 through 1988 was 520,439 ounces of gold; mill grade reserves (avg. 0.317 oz/ton gold) are 1,081,000 ounces and heap leachable reserves (avg. 0.021 oz/ton) are 942,000 ounces gold (AMAX Gold, 1989). The estimated total gold content, 2,543,439 ounces, does not include known deeper extensions of vein and breccia mineralization that continues below the currently planned open pit.

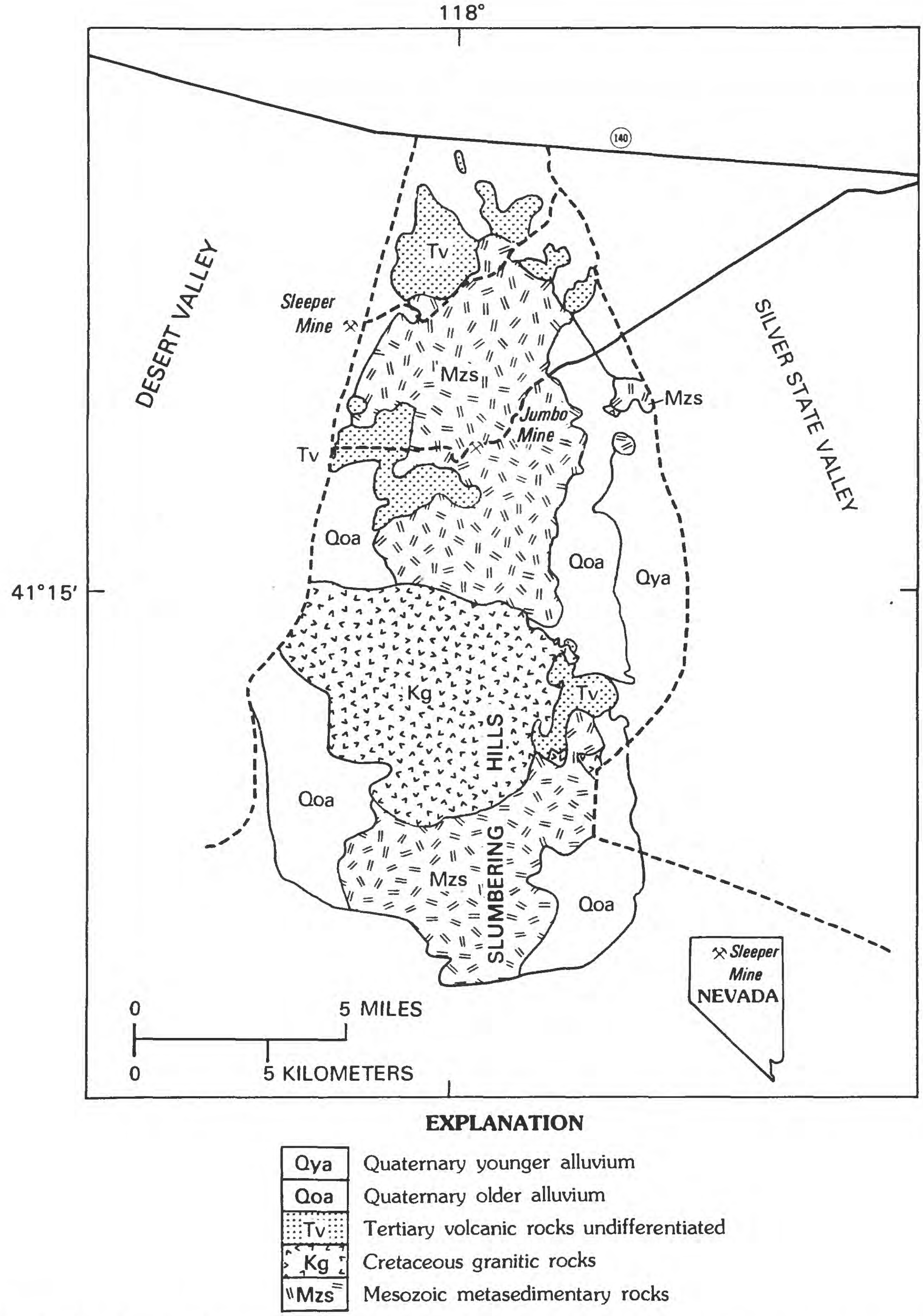


Figure 1. Location and geologic setting of the Sleeper mine, Humboldt County, Nevada. Regional geology simplified from Willden (1964).

Mining and Exploration History

Previously recognized ore deposits in the Slumbering Hills (Awakening district) were chiefly gold-quartz veins in Mesozoic metasedimentary rocks. Production was first recorded in 1914 but did not become significant until 1936 when the Jumbo deposit was discovered (Willden, 1964). The Jumbo mine worked adularia-quartz veins by underground and open-pit methods. The age of the Jumbo veins is not known. Total recorded production for the district through 1963 was slightly less than $1,000,000 (Willden, 1964); there has been modest production of gold from the Jumbo mine since then.

The standard topographic map (USGS Jackson Well, 1:24,000, 1982) shows 2 shafts, 3 adits, and 17 prospect pits within 2 km of the Sleeper mine. These workings, probably from the 1930's, are in or adjacent to altered and veined Tertiary rocks. A shaft now covered by the Sleeper mill served a crosscut heading east into altered volcanic rocks; if the crosscut had been driven westward about 50 m, it would have encountered the Sleeper discovery mineralization.

The Sleeper prospect was located by John Wood of AMAX Exploration, Inc., who spotted a scarp stained with iron oxides during an aerial reconnaissance program in early 1982. Followup ground mapping and sampling indicated a potential for epithermal precious metals (Wood, 1988). A pediment exposed altered volcanic rocks, which had been prospected previously. For 2 years the AMAX team tracked geochemical and geologic indications of gold-silver mineralization with 3,536 m of core and reverse circulation drilling to outline a zone of low-grade (c. 0.04 oz/ton gold) mineralized volcanic rock. Step-out drilling through alluvial cover west of the pediment eventually brought success. Drill hole 34 penetrated 102 m of silicified breccia that averaged 28 g/t gold and 62 g/t silver, and one vein containing visible, very high grade gold. With that encouragement, drill activity was increased, and in 6 months a "probable" mineable reserve of 1.45 short tons averaging 0.32 oz/ton gold and 0.90 oz/ton silver was defined. Stripping of overburden started in June 1985, mining in January, 1986, and milling began in February, 1986. The sleeping giant of Slumbering Hills was awake after 4 years of exploration and development.

The Sleeper ore is not just high grade, it also is amenable to low-cost mining and milling. The pervasively fractured ore is more easily blasted, mined, and crushed than if it were still a tough siliceous mass. Also, the upper 30-75 m of the ore body is oxidized and consumes little cyanide in heap leaching. High-grade ore contains gold coarse enough for gravity recovery, a circuit that accounts for about 20 percent of gold production. Overflow is cyanide leached with high recovery despite some ore with high sulfide content. Neither encapsulation of gold in silica nor presence of sulfides have been a significant problem, and clay content of high-grade and leach ores is generally low. Milling is not optimized for silver, but approximately equal amounts of silver and gold are recovered.

GEOLOGIC SETTING

Regional Geology

The oldest rocks in the area (fig. 1) are Triassic and Jurassic(?), dark, fine-grained slate, phyllite, quartzite, and calcareous phyllite of the Auld Lang Syne Group (Willden, 1964; Burke and Silberling, 1973). These miogeoclinal sedimentary rocks were folded, faulted, and regionally metamorphosed to greenschist facies during the Mesozoic. A large granodiorite and monzonite stock intruded the metasedimentary rocks during the Cretaceous and occupies the central part of the Slumbering Hills (Willden, 1964). Tertiary volcanic rocks unconformably overlie the Mesozoic rocks, chiefly in the northern part of the range. Most of the volcanic rocks are outflow facies of the McDermitt Volcanic field and its nested calderas about 55 km to the north (Rytuba and McKee, 1984). Large volumes of peralkaline ash-flow tuffs were erupted from the McDermitt calderas from 16 to 15 Ma. A younger, local volcanic complex (described later) also is present and was important in localizing the Sleeper deposit. Extensional tectonism started at about 16 Ma and continued through Basin and Range-type block faulting about 8 Ma (Rytuba, 1989a). High angle, extensional fractures and faults were crucial for the development and preservation of the Sleeper deposit.

Local Geology

The low hills east of the mine (fig. 2) are underlain chiefly by Triassic and Jurassic(?) slate, phyllite, and calcareous phyllite. Much of this basement has subdued topography and is mantled by a foot or more of Quaternary aeolian sand that greatly hampers geologic mapping. Tertiary volcanic rocks overlie and intrude the metasedimentary basement. A preliminary Tertiary section compiled from the 1:12,000 scale mapping of Joe Bottero (AMAX Exploration, Inc., unpub. map, 1988) and reconnaissance studies by J.J. Rytuba contains six major Tertiary units. 1) The basal Tertiary unit comprises basaltic and andesitic flows and related dikes. Volcaniclastic or lacustrine sedimentary rocks are locally exposed at the top of this unit. 2) An older welded tuff sequence of andesite-dacite composition is probably correlative with the 24 Ma Ashdown Tuff (Rytuba, 1989b). The tuffs contain distinctive plagioclase phenocrysts, sparse pyroxene and quartz phenocrysts, and many have a glassy matrix. Units 1 and 2 are well exposed on the steep slopes of a prominent peak (locally known as "ZZ Top"), 2 km southeast of the mine (fig. 2). 3) Intermediate lavas, bentonite, and thin conglomerate beds comprise a unit that is poorly exposed. The 16.1-Ma Steens Basalt, a unit containing distinctive coarse plagioclase phenocrysts that has widespread distribution to the north and northwest (Rytuba and McKee, 1984), is probably represented in this unit; it has been recognized only in float and in drill cuttings which are too fine to reliably sample large phenocrysts. 4). Rhyolite ash-flow tuffs, two vitrophyres, and light-colored air-fall tuffs are part of a younger, peralkaline tuff sequence. These rocks are well exposed on the cuestas 2-3 km northeast of the mine (fig. 2). The younger ash-flow tuffs are light bluish gray, densely welded and locally flow-folded, and have a distinctive parting parallel to layering that probably reflects vapor-phase alteration. Their chemistry and lithology (Nash and Rytuba, unpub data, 1989) are similar to those of the peralkaline tuffs of Oregon Canyon (16.1 Ma) and Long Ridge (15.6 Ma) (Rytuba and McKee, 1984; Rytuba, 1989b). 5) Rhyolite porphyry dikes, domes, and flows of a local volcanic complex comprise most of the rock exposed in the pits and are the main hosts for ore. These rocks have distinctive coarse stubby plagioclase and sanidine phenocrysts, smaller resorbed quartz eyes and sparse biotite phenocrysts; the chemistry of this unit is summarized in table 1. The aphanitic matrix is generally altered, but local zones having glassy matrix have been intercepted in drill holes 300 to 500 m west of the pits. The round hill 1 km southeast of the mine (fig. 2) provides a good exposure of a rhyolite dome with dikes and possible lateral flows; in this area flow banding and flow breccias are well developed, unlike

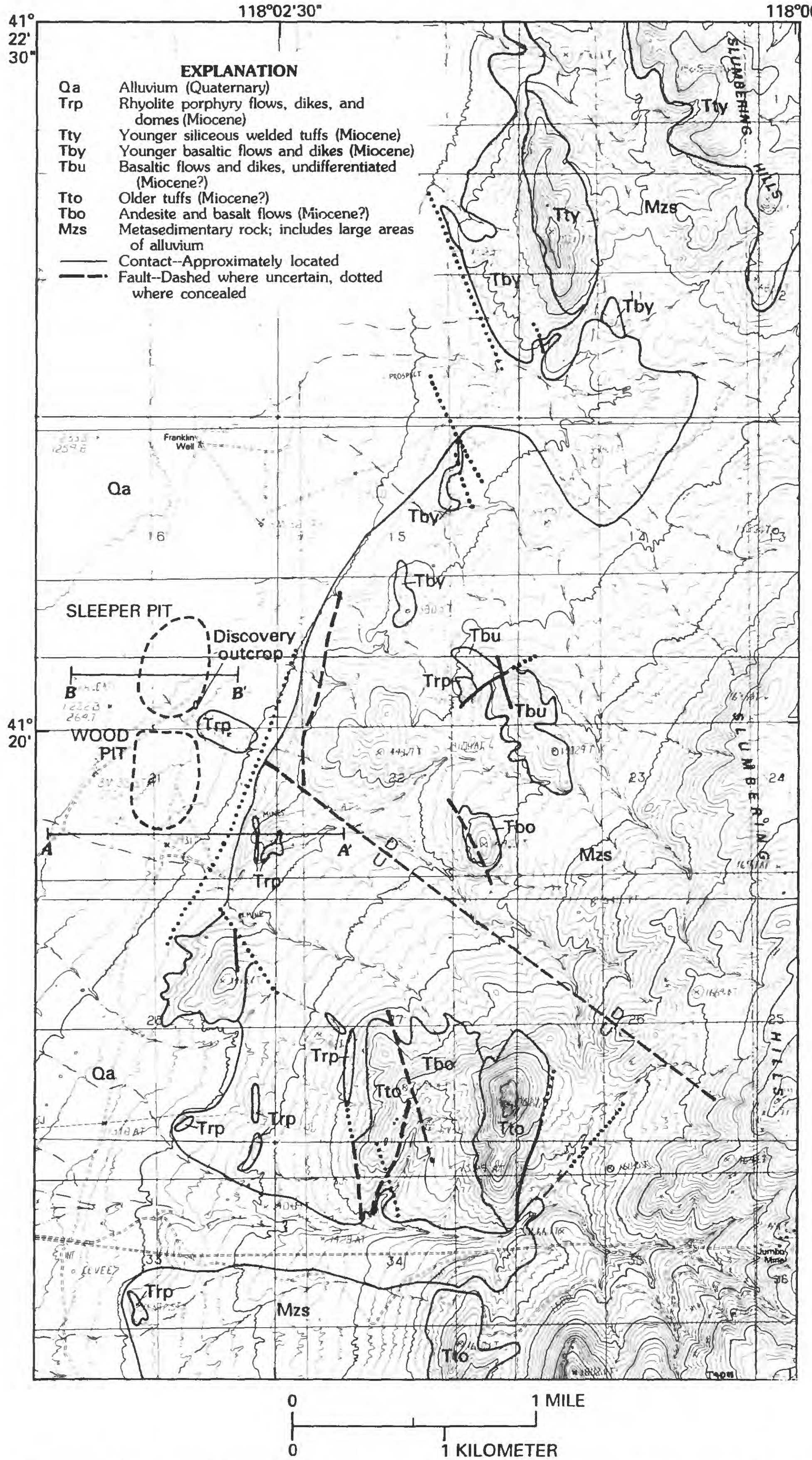


Figure 2. Generalized geology of the area of the Sleeper mine and the western foothills of the Slumbering Hills. (Simplified from J. Bottero, unpub. map, AMAX Exploration, 1988.)

rhyolite porphyry in the pits that only rarely display these features. Many old prospects east of the Sleeper mine worked veinlets in altered rhyolite dikes. 6) Dark, aphanitic basalt dikes and flows make up the youngest unit. These rocks were thought to be post-ore and of possible Pliocene age by Wood (1988).

Alluvial deposits cover the Sleeper gold deposit and also mantle most of the foothills to the east. Several types of alluvium are present but will be discussed only briefly here. Older alluvial fan deposits in the hills are truncated by a scarp at elevations of 1320-1340 m that probably is a wave-cut surface from Pleistocene Lake Lahontan (Willden, 1964). The lower valley floor is underlain by younger alluvium that includes a variety of unconsolidated coarse alluvial gravel and well-bedded, fine-grained lacustrine sand and clay. Drilling and seismic surveys indicate that the bedrock surface slopes gently to the west for several kilometers before plunging to much greater depths in the middle of Desert Valley. Approximately 20-50 m of alluvium covers the Sleeper orebody (fig. 3). Gravel beds 0-10 m above the disconformity contain enough gold to merit mining in some places; also present are boulders of laminated siliceous rock that resemble sinter and are unlike any of the silicified bedrock yet exposed by mining.

Structure of the Tertiary rocks is poorly known, mainly because aeolian sand covers key contacts. Layered volcanic rocks typically dip 30° to 70° to the east, but locally dip to the west. Some dips reflect rheomorphic folding of the very hot ash-flow tuffs, but most of the eastward dips reflect rotation during extensional faulting. Tertiary rocks are cut by faults having a wide range in strike that Rytuba (1989b) suggests may reflect the doming effect of a buried intrusion. Dikes tend to strike close to due north. Electromagnetic surveys suggest the presence of several northwest-striking faults (Wood, 1988; fig. 2) that are consistent with downdropping of units from south to north, but these poorly exposed structures are not well understood. One or more rhyolite intrusions may have vented flows to the surface. The present land surface in the foothills probably has changed little since the Miocene.

Normal faults on the west side of the Slumbering Hills that formed during Basin and Range tectonism have relatively small displacement (fig. 3) judging from geomorphology and measurable offsets, unlike some range front faults in Nevada having displacements of thousands of meters. Larger offsets probably would have dismembered the gold deposit rendered it uneconomic. The elevations of the pre-Tertiary disconformity in outcrop and in drill intercepts and the textural similarity of rhyolite porphyry in the Wood pit to that in the foothills suggest that the Sleeper deposit was downdropped about 300-600 m.

Mine Geology

The Sleeper and Wood pits expose two highly fractured and altered Tertiary volcanic units that are disconformably overlain by Pleistocene gravel and sand (figs. 4-5). The major Tertiary unit is rhyolite porphyry. Plagioclase, sanidine, and quartz phenocryst abundances and textures are very similar over much of the Sleeper pit and all of the Wood pit despite variable hydrothermal alteration. Although this rhyolite porphyry is very similar to several bodies exposed 1-2 km to the east (fig. 2), it only rarely displays the flow banding and brecciation of the latter; hydrothermal alteration possibly obscures primary fabrics. At least one dike-like body of porphyry occurs in the Sleeper pit, and others are suspected from drill cuttings. Much of the subsurface east, south, and west of the Wood pit is rhyolite porphyry,

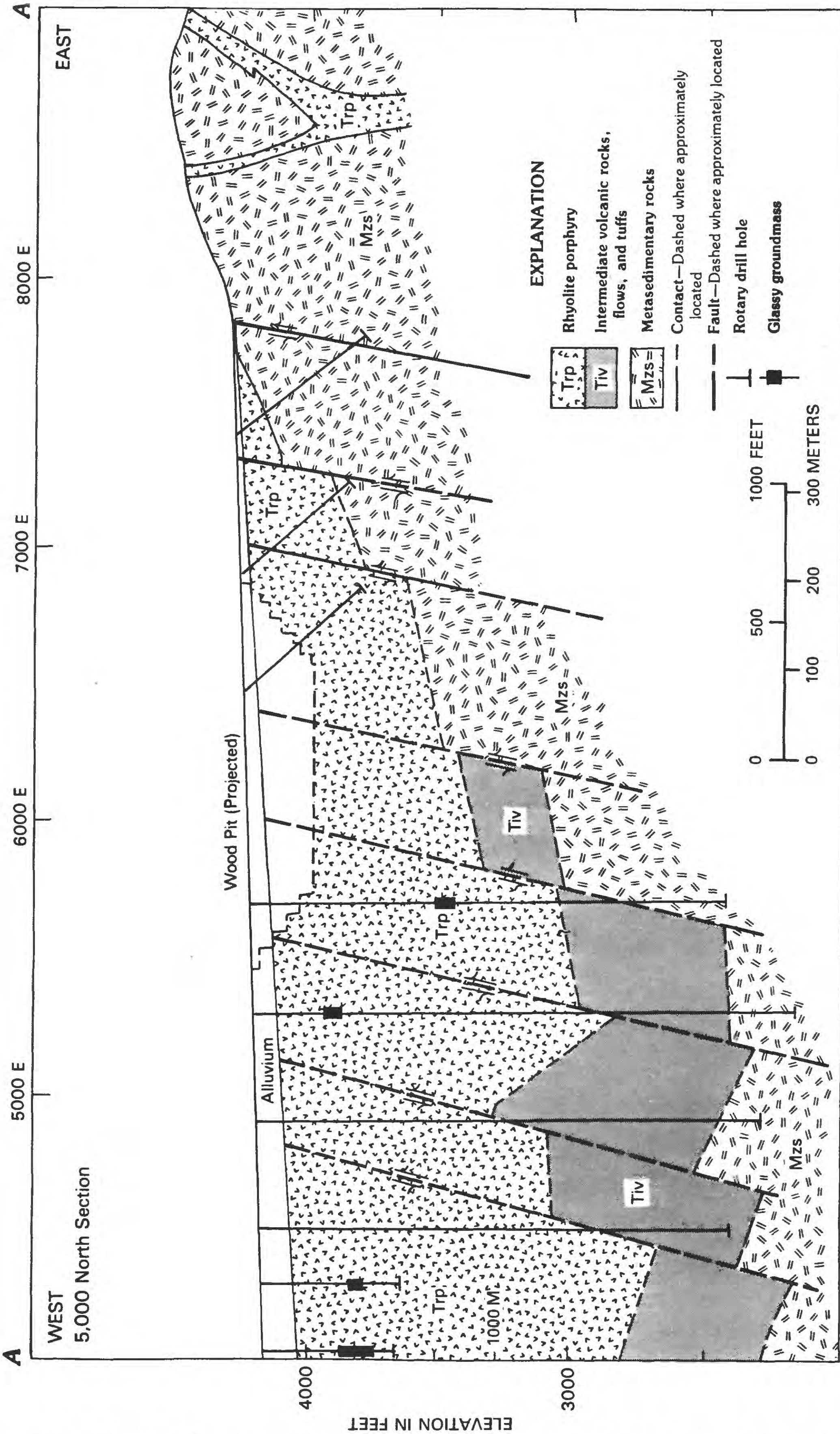


Figure 3. Generalized east-west geologic cross section through the Sleeper mine and range front. The range front contains many more normal faults than shown; eastern extent of intermediate volcanics in subsurface is not known. Line of section is shown on figure 2.

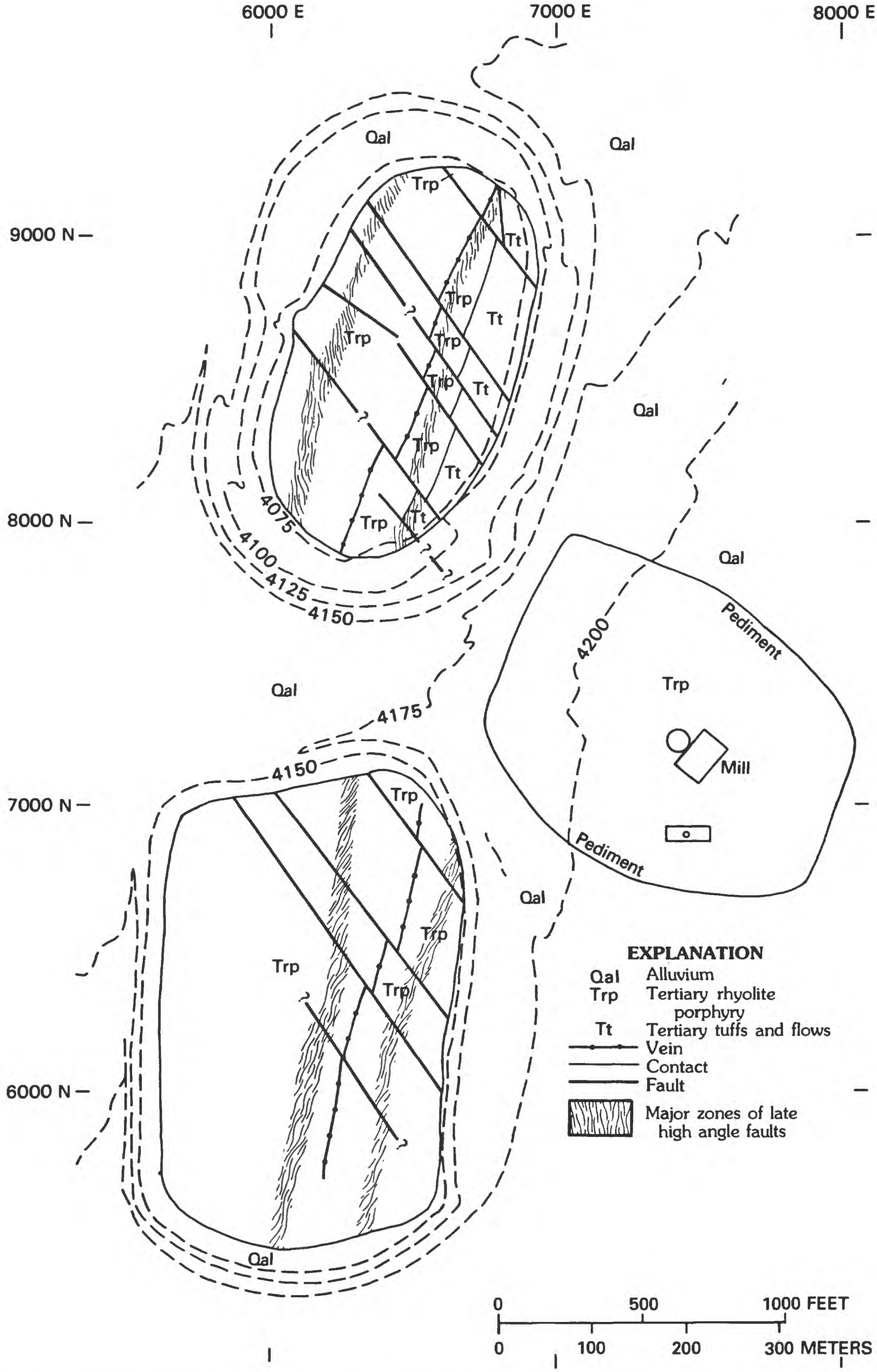


Figure 4. Generalized geology of the Sleeper mine. Individual post-ore normal faults cannot be shown at this scale.

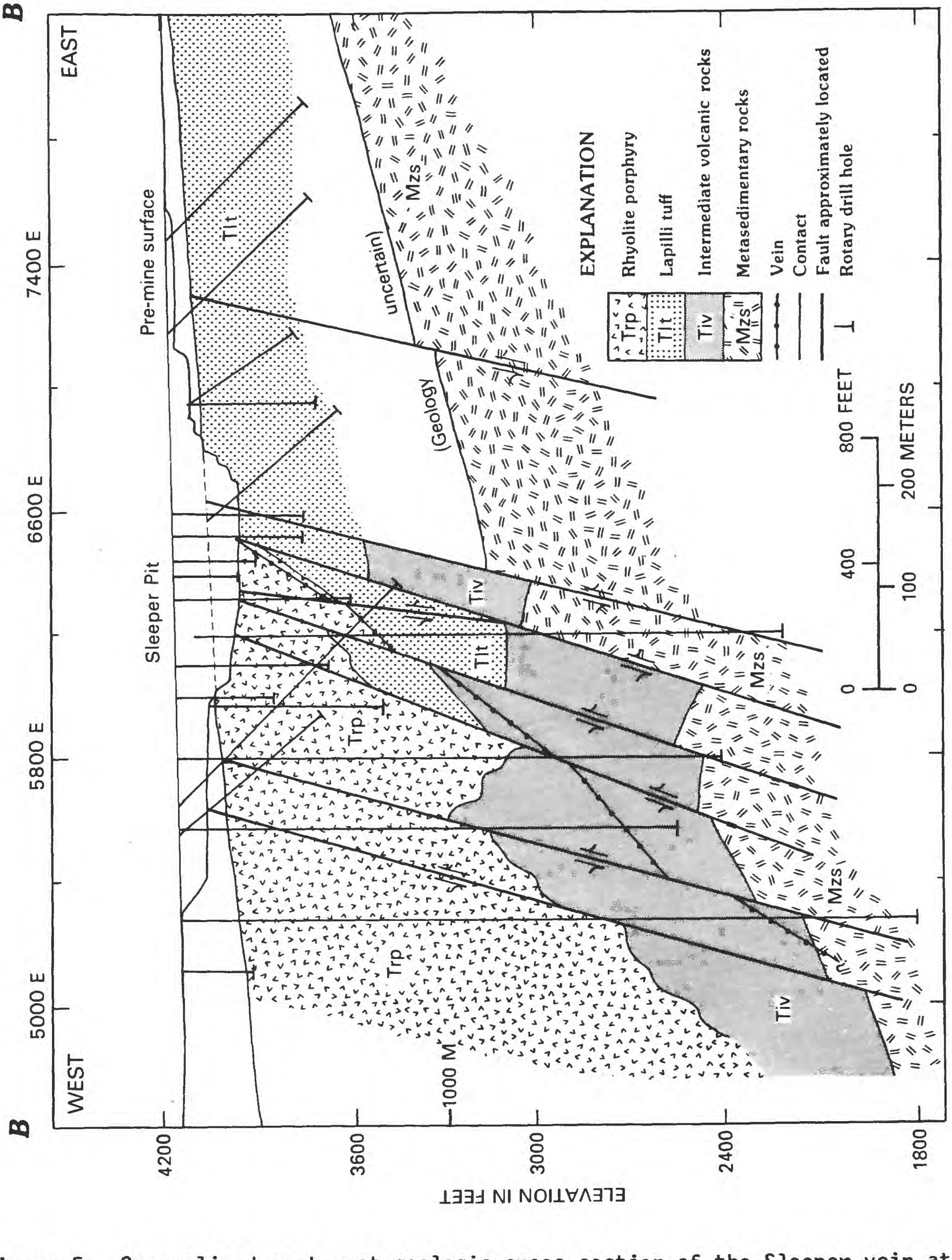


Figure 5. Generalized east-west geologic cross section of the Sleeper vein at 8,600 ft north. Structure below 3,800 ft elevation is ambiguous but probably is dominated by high angle normal faults. Line of section is shown on figure 2.

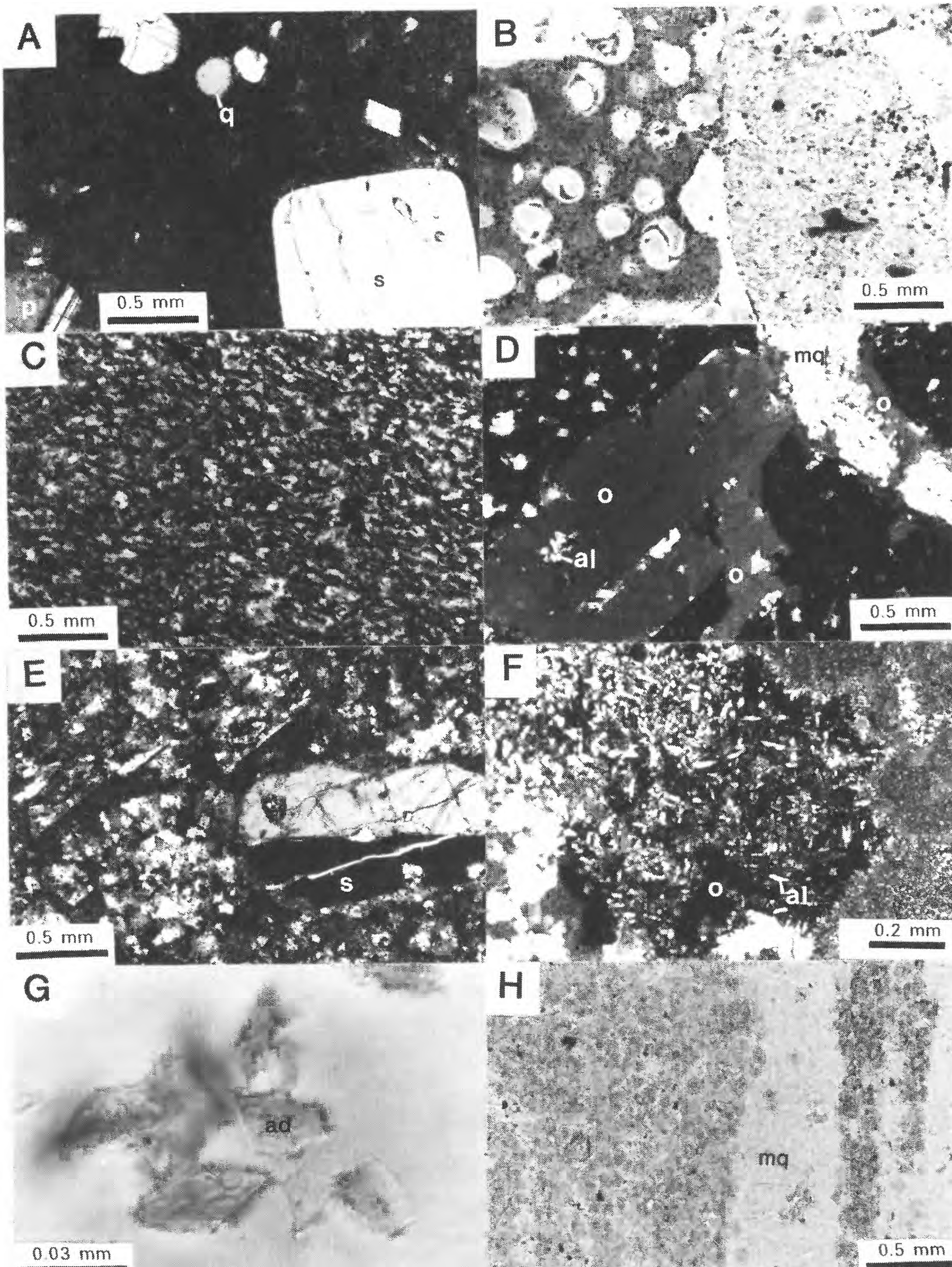
but fabrics can not be ascertained from drill cuttings to determine intrusive or extrusive character. Many drill holes on the western flank of the mineralized and altered zone (>300 m west of the pits) intercepted glassy rocks having phenocrysts that resemble those in the rhyolite porphyry. Chips with black vitreous matrix are typically present across 4.6 to 10.7 m intervals, but some predominate for as much as 50 m. These glassy intervals seem to be too thick to be a vitrophyre and do not occur adjacent to a lithologic contact (fig. 3). The glassy porphyritic lithology seems to grade into more typical silicified or argillized rhyolite porphyry, but relations are equivocal in composite cuttings representing 1.5 m (5 ft) intervals. The black glassy chips are variably altered and mixed with chips that are pale green to cream colored and very hard (silicified?). Severe alteration and lack of diagnostic evidence on fabrics in cuttings hamper conclusive characterization of the rhyolite porphyry. The known lateral extent is more than 2,100 m N-S by 1,500 m E-W, and 350 m vertically. Tentatively, the porphyry unit is considered to be partly an intrusion (dome?) and partly flows.

The other Tertiary unit, exposed only in the east wall of the Sleeper pit, comprises a variety of layered volcanic rocks of intermediate composition. These probably were flows, flowbreccias, air-fall tuffs, and lapilli tuffs from nearby vents. Compositions have been changed substantially by hydrothermal alteration but probably were dacitic (that is, moderately mafic; table 1.). Dikes of rhyolite porphyry intrude the dacite flows and tuffs, but the main rhyolite dome(?) is in fault contact with dacite flows and tuffs. Beds and compositional layering in dacite flows and tuffs strike north-south to N.40° W. and dip about 70° E.; the Tertiary rocks are fractured throughout the pits, and are cut by several prominent north-striking normal (range front) faults with up to 20 m of clay gouge.

The rhyolite porphyry, mapped through 5 benches (30.5 m, 100 ft), generally has massive fabric and uniform primary texture (figs. 6A,D,E), although alteration has dramatically changed its appearance and composition at most places. Flow foliation is visible at a few localities. In the Wood pit weathering brings out large (meter scale) bulbous swirls enhanced by iron oxides that are possibly a reflection of perlitic cracks. Phenocryst abundances are consistent across large areas, and compositional layering has not been recognized. Plagioclase phenocrysts comprise about 20-25 percent, sanidine 5 percent, and quartz 3-5 percent. The massive character and apparent compositional uniformity (allowing for alteration) of the rhyolite porphyry for hundreds of meters laterally and for more than 300 m vertically (fig. 5) is the main basis for calling it an intrusive rock. Silicification in ore zones preserves primary textures (fig. 6D). Although peripheral argillic alteration produces crumbly rocks that appear to comprise a different unit, phenocryst assemblages appear to be the same throughout. Most contacts with older rocks observed in pit walls and inferred from drill cuttings are faults. Surface exposures of rhyolite porphyry in the foothills commonly show flow banding or flow breccia, fabrics that cannot be discerned in cuttings. Thus, we do not know how much rhyolite was emplaced as flows on the flank of the postulated exogenous dome.

Tertiary pyroclastic rocks of many types are widespread in northwestern Nevada (Rytuba and McKee, 1984) and many geologists have called the rhyolite porphyry at Sleeper a crystal tuff. Although this is possible, important diagnostic evidence has not be found to support that origin. Macroscopic and microscopic evidence for pyroclastic character or pumice fragments (Ross and Smith, 1961) have not been recognized; because silicification preserves other

Figure 6. Photomicrographs of host rocks, alteration, and veins (next page). **A**, Rhyolite porphyry having typical coarse sanidine (s) and plagioclase (p) phenocrysts and smaller quartz eye (q) set in aphanitic groundmass (crossed polarizers). **B**, Lapilli tuff containing large lithic clasts and vesicles filled with opal (transmitted light). **C**, Aphyric dacite flow with trachytic texture (crossed polarizers). **D**, Altered rhyolite porphyry in which opal (o, dark) and minor fine alunite (al) replace groundmass and plagioclase, cut by stockwork veinlet of microquartz (mq) and opal (o) (crossed polarizers). **E**, Altered rhyolite porphyry with fresh sanidine phenocrysts (s) and sericite-quartz groundmass (crossed polarizers). **F**, Very fine-grained alunite lathes (al) and opal (o) in plagioclase sites (crossed polarizers). **G**, Rhombs of fine adularia (ad) in banded gold-quartz vein (transmitted light). **H**, Banded quartz vein with layers of dusty grains that are quartz pseudomorphs of possible fine calcite (transmitted light).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textures in the rhyolite porphyry, some textures indicative of pyroclastic character should have survived alteration. Some rare feathery fabrics in drill core resemble stretched and compacted pumice, but this has not been confirmed in thin sections.

Layered dacitic tuffs and flows exposed in the eastern wall of the Sleeper pit are mostly lapilli tuffs containing 20-50 percent, 1-3 cm-size, angular to rounded fragments of light-colored pumice or dark rock (fig. 6B). The lapilli tuff, in fault contact with rhyolite porphyry (and internally faulted), is about 60-m thick in the southeastern wall of the Sleeper pit. Some very soft, clay-rich layers of possible air-fall tuff are interbedded with the lapilli tuff. Fragment size decreases in the upper part of the unit, near the transition to aphyric flows (fig. 6C) in the northeast corner of the Sleeper pit. Chemical and petrographic data suggest that these rocks of diverse texture had a common origin. Microphenocrysts of tabular plagioclase 100-200 μm long by 30-50 μm wide are the only phenocrysts observed and are present in both lapilli tuffs and flows. Flows contain vesicles, generally filled by microcrystalline quartz, and microphenocrysts aligned in a trachytic texture (fig. 6C). Chemical analyses (table 1) indicate high concentrations of a "mafic" suite of elements (Fe, Ti, Cr, Ni, Sc, and V) and low concentrations of "felsic" elements such as Nb, Th, and Zr. Although concentrations of most major elements were significantly changed during alteration, ratios of probably immobile elements Ti, Zr, Nb, and Y suggest that original bulk compositions were in the andesite-dacite range. Some darker clasts may be more mafic, perhaps basaltic, and fragments of light-colored pumice probably were rhyolitic. The abundant vesicles and coarse size of fragments suggest that these flows and tuffs probably came from a nearby vent.

Deep drill holes intersected volcanic rocks of intermediate and felsic composition and of uncertain stratigraphic position at depths of about 300-600 m (fig. 5). Cuttings show aphyric to sparsely porphyritic textures, and many intervals are rich in clay. Because macroscopic textures and fabrics are not represented well in cuttings, correlations with exposed rocks are difficult. Studies in progress will attempt to establish the stratigraphy and composition of these rocks. Preliminary studies show that the clay mineralogy is variable and the same as in exposed alteration zones, and that chemical compositions are highly variable (e.g., wide range in Al and Ti concentrations).

Faults of several orientations are the dominant structural features of the mine area. Ore is clearly fracture controlled, but there is little evidence for pre-mineralization displacement along these fractures. All faults with measurable offset, and the majority of fractures, are post-ore. The oldest faults in Tertiary rocks normal (range front) faults that strike about N. 10° E. and dip 50° to 70° to the west. The high-grade veins occupy fractures that have nearly the same orientations as the range front faults; the veins consistently strike N. 30° E. and dip 60-65° NW. A few post-ore faults that strike northwest are filled by barren quartz as much as 1-m thick. Unhealed faults and fractures have steep dips and diverse strikes, most commonly N. 30° E., N. 30° W. and due north to N. 10° E. The larger range-front faults strike about N. 5° E., dip about 75° W., and create gauge zones as much as 20-m thick; magnitude of offsets are difficult to determine in the pit rocks but must be about 100 m (figs. 3, 5). A few splays from range front faults dip about 45° E. Wall rocks and ore are broken into centimeter-size fragments in zones of intersecting fractures. Most of these late fracture surfaces are coated with red to brown earthy iron oxides that give the prominent red color to the upper part of the two pits. These fracture zones appear to narrow downward and are tight about 30 m below the disconformity. Offset along the late faults is generally less than 3 m on individual fault surfaces, but a few offsets of as much as 6 m have been noted (fig. 4); sense of displacement could be lateral, vertical, or a combination of both. Some of the north- and northwest-striking faults were the sites of acid leaching and subsequent infilling by opal and white to brown alunite-jarosite. This late-stage alunite has been dated at 6 Ma by K/Ar methods (E.H. McKee, oral commun., 1988). Recent renewed movement on some range-front faults is indicated by displacement of Pleistocene sediments.

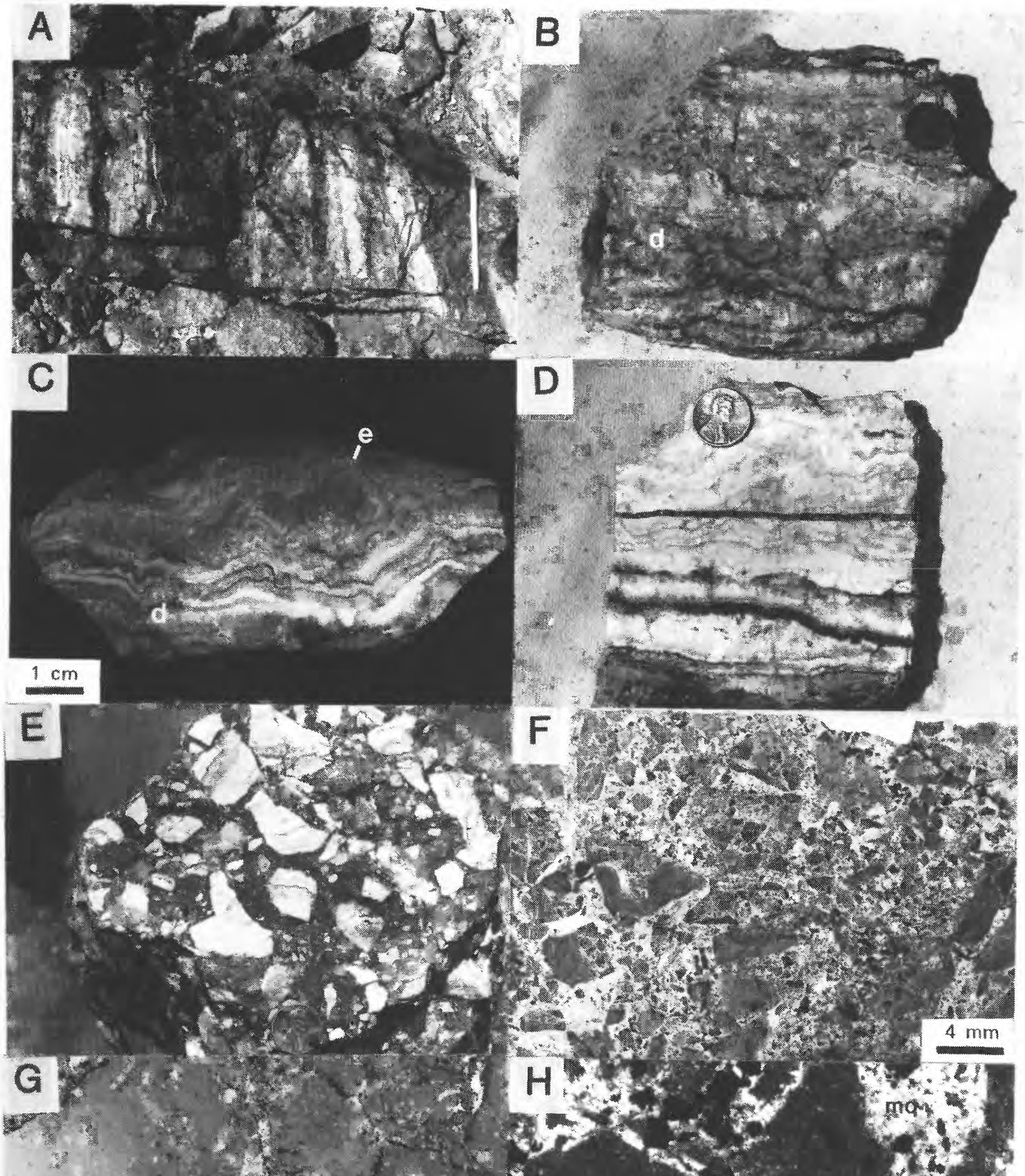
Breccias and stockworks cemented by silica-pyrite-marcasite and containing variable amounts of silver and gold occur adjacent to the veins and in broad areas of the hanging walls. The stockworks and breccias probably are related because the two structures are gradational; differences are chiefly the amounts of matrix or cementation, which reflect the amount of dilation. Breccias are clast-supported rocks with about 15-30 percent matrix comprised of fine rock particles and hydrothermal cement. Stockworks are fractured rocks cut by numerous thin veinlets (<1 cm) of random orientation. Some breccias may be related to faults, but most appear to be erratic local structures having no displacement. Breccia zones generally are 0.5-5 m wide, but stockwork zones extend for hundreds of meters, especially in the hanging walls (west) of the veins. Breccias invariably contain only fragments of adjacent rocks. Banded quartz vein fragments in some breccias indicate those breccias are younger than the veins, whereas other (older) breccias are cut by banded gold-quartz veins. Breccias and stockworks are flooded by silica and pyrite, but there is no apparent reaction selvage around fragments or veinlet walls.

A key feature of the Sleeper deposit is the superposition of multiple, structurally controlled stages of mineralization. We infer the presence of an ancestral fracture zone that established the location of pre-vein silicification and brecciation. Once established, the zone of early silicification became the locus for repeated brittle fracturing for veins, stockwork veinlets, and breccias. Silicified rhyolite porphyry was most favored for the brittle deformation, but layered dacitic tuffs and flows that were previously silicified also were fractured and mineralized.

ORE DEPOSITS

Three types of gold-silver ore are mined at Sleeper: high-grade veins, medium-grade breccias, and low-grade stockworks (fig. 7). The high-grade veins (figs. 7A-C) are banded quartz-adularia-gold/electrum veins with minor carbonate, barite, and late stibnite (Saunders and others, 1988). Assays are as high as 195 oz/ton gold over a 6.1-m (20-ft) vertical blasthole or 162 oz/ton gold for a 1.5-m interval (true thickness) of reverse circulation cuttings; Ag/Au ratios are 1 or less. The veins contribute more than 60 percent of reserves. Breccias (figs. 7E-G) cemented by silica, pyrite, and minor adularia typically contain 0.1 to 1 oz/ton gold; Ag/Au ratios are in the range of 3-6. Breccia ore generally is within 5 m of high-grade veins but also occurs as discrete zones several meters wide in both footwall and hanging wall rocks. Approximately half of the breccia ore, chiefly that near veins, is processed through the mill. Stockwork ore containing numerous 1 to 10 mm-wide quartz-pyrite veinlets (fig. 7H) generally carries less than 0.1 oz/ton gold; Ag/Au ratios are about 10. The stockwork ore is bulk mined for heap leaching and occurs over broad areas of both Wood and Sleeper pits, particularly in the hanging wall. Although Sleeper is famous for its

Figure 7. Photographs of veins, breccias, and stockworks (next page). **A**, Portion of Wood vein, about 70 cm wide, with three intervals of banded vein. **B**, Banded vein showing fine and disrupted (d) bands; sample 18 cm wide. **C**, High-grade vein sample showing fine and disrupted (d) bands and layers rich in electrum (e). **D**, Banded quartz vein showing later dark-colored quartz stage and cross-cutting stockwork veinlet. **E**, Hydrothermal breccia with fragments of vein quartz and dark silica-pyrite matrix (sample is 17 cm wide). **F**, Hydrothermal breccia having angular fragments of silicified porphyry in matrix of fine rock fragments and silica (transmitted light). **G**,. Hydrothermal breccia with angular and subrounded fragments cemented by silica-pyrite (transmitted light). **H**, Stockwork veins of microquartz (mq) and pyrite (py) in rhyolite porphyry (transmitted light).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spectacular vein ore, low grade heap leach ores containing 0.01-0.04 oz/ton also are significant. The expanded pit and leach pads will produce almost a million ounces of gold, largely from these low-grade stockwork ores.

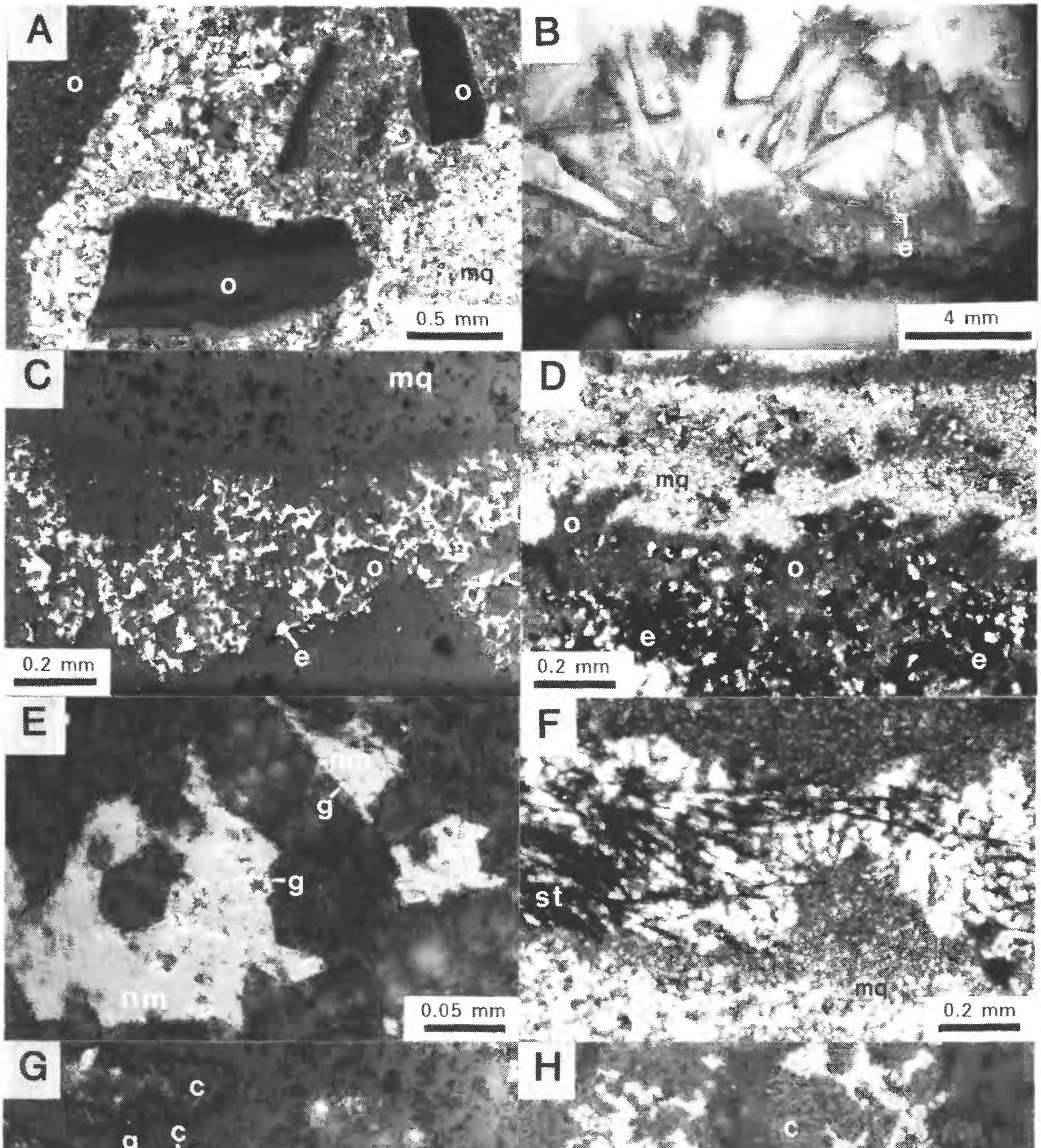
High-grade (Bonanza) Veins

Banded high-grade veins range from a few centimeters to 5-m thick (figs. 7A-C). Although post-ore faults offset these veins, detailed drilling and pit mapping show that the trends are quite consistent along strike for distances of more than 200 m (fig. 4), and downdip for more than 200 m (fig. 5). Veins occur in a zone at least 450-m wide and more than 1,200-m long. In most pit exposures a series of parallel (sheeted) quartz veins (fig. 7A) occur in a zone 10 to 25 m wide; intervening wallrocks are medium-grade breccias and stockworks. Scattered veins less than 0.5-m thick in the hanging wall possibly are branching splays of the main, west-dipping vein system (Saunders and others, 1988). Ore delineation (reverse circulation) drill fans 9.1 m apart, inclined 45° to 75° to the east, provide details on veins for mining and ore reserve calculations. High-grade veins are recognized in cuttings by identification of vein quartz that often contains visible gold. The limited amount of deep drilling and complex structure do not permit assessment of reserves below the 3560 bench (pit depth 183 m), but there are significant intercepts more than 300-m deeper. The downdip continuity of these veins is more than 500 m, which is comparable to epithermal gold-quartz veins in other volcanic fields such as the San Juan Mountains of Colorado (Nash, 1975) and the Republic District of Washington (Full and Grantham, 1968). The amount of vein removed by erosion cannot be determined directly, but is inferred to be relatively small because only the basal alluvial deposits contain eroded vein clasts.

The banding of ore and gangue minerals in high-grade veins (figs. 7A-D; 8C-D) provides an excellent framework for paragenesis of vein substages. As many as 30 bands of silica and electrum have been counted in hand specimen, so hundreds of bands must exist in the wider, highest-grade vein segments. Individual bands, generally less than a few millimeters thick, tend to be mono- or bi-mineralic. Some bands are estimated to contain as much as 50 volume percent electrum (figs. 8C-D). The electrum bands are separated by one or more bands of silica that contain little or no electrum and rarely any sulfide minerals. Indeed, minerals other than silica and gold-silver minerals are rare in the gold-rich layers. Fine-grained adularia (fig. 6G) and minor amounts of barite are present locally in either silica or electrum bands. The later part of the main-stage banded silica-electrum veins contains small amounts of argentite, miargyrite ($AgSbS_2$), tetrahedrite, Ag-Se and Ag-Te minerals, pyrite, and rutile. No pyrite or marcasite has been observed in the gold-silica bands. The early silica is generally milky or gray, in contrast to later stages that commonly are dark gray to black.

Middle vein stages are disrupted and broken (figs. 7B,D; 8A) rather than systematically banded. Fragments of veins from 2-mm to about 3-cm wide are angular to subround, and many appear to be bent. Many of the fragments seem to have been soft when broken off the vein walls. Rock fragments are generally rare. The vein fragments are cemented by silica which may contain electrum. Deposited on top of the broken parts of the high-grade veins are dark-gray to black silica layers that contain abundant Ag-Se minerals, sphalerite, and fine-grained framboidal pyrite. Veinlets containing relatively coarse-grained naumannite (Ag_2Se; fig. 8E) cross-cut silica-

Figure 8. Photomicrographs of gold veins (next page). **A**, Fragments of banded opal (o) enclosed in microquartz (mq) (transmitted light). **B**, Blades of former calcite(?) replaced by quartz; fine electrum (e) is dusted on blades (reflected light). **C**, Fine banding of electrum (e) and microquartz (mq) (reflected light). **D**. Fine banding of electrum (e), microquartz (mq, clear), and opal (o, dark); approximately same area as shown in C (transmitted light). **E**, Naumannite (nm) rimmed by supergene gold that has little Ag (reflected light). **F**, Needles of stibnite (st) in microquartz (mq) (transmitted light). **G**, Naumannite (Nm) in microquartz and vug-filling supergene gold (g) and cerargyrite (c) (reflected light). **H**, Naumannite (nm) rimmed by supergene gold (g) with cerargyrite (c) in void (reflected light).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electrum bands and probably are part of the middle stage. Paragenetically similar veinlets also contain an unnamed antimony selenide with the approximate composition SbSe. The latest stages, found at scattered localities, are veinlets or bands with coarse stibnite (fig. 8F) and silica that is more coarse-grained than in earlier stages.

Carbonate minerals may have been part of the early stage but now are represented by tabular forms (fig. 8B) replaced by silica. Only the forms survive; no highly birefringent grains or inclusions have been seen. The tabular form resembles platy calcite in other precious metal veins and especially that described as "angel wings" (Vikre, 1985) from the National District. Barite also has this habit in many epithermal veins. Gold and silver minerals locally are concentrated along the outer margins of the tabular pseudomorphs (fig. 8B) and generally decrease in abundance toward the centers. Other tetragonal and hexagonal forms less than 20 μm in diameter on growth bands in siliceous layers (fig. 6H) may have been fine-grained carbonate minerals.

Electrum from the high-grade veins has a relatively uniform composition, approximately 69 weight percent gold and 31 weight percent silver, according to electron microprobe analyses. Electrum or native gold with a more yellow color and low silver content is interpreted to have been modified or deposited by supergene processes (Saunders and others, 1988). Associated hypogene silver minerals in the high-grade veins are miargyrite, acanthite, and naumannite.

Breccia and Stockwork Ores

Siliceous breccias and stockworks constitute an important part of the Sleeper orebody. These ore types are notably richer in pyrite-marcasite and have higher silver/Au ratios than the high-grade veins. The breccias are mostly clast supported and have approximately 15-30 percent matrix comprised of very fine grained silica and pyrite-marcasite (figs. 7E-G). Clasts are almost always monolithologic and the same lithology as nearby unbrecciated hosts. Angular clasts range from about 30 cm to fine "rock flour" (<0.1 mm) in the matrix (figs. 7F,G). The breccia zones are generally 1-3-m wide and grade laterally into less brecciated wall rock cut by stockwork veins that fill dilatant structures. At some localities it has been possible to determine multiple stages of brecciation as evidenced by cross-cutting realtions or presence of breccia clasts in breccia. No displacement is associated with the breccia zones. These features are characteristic of hydrothermal rather than tectonic breccias (Nelson and Giles, 1985; Wood, 1988).

Ore-bearing breccias are invariably siliceous and much richer in sulfide minerals than the veins. Breccias typically contain 5-10 percent sulfide as matrix cement, which gives the matrix its characteristic dark color. One variety of black matrix contains abundant stibnite. Microscopically, the iron sulfide minerals are very fine (10-30 μm), euhedral crystals. Larger crystals display pronounced anisotropy characteristic of marcasite, and those too small for reliable optical tests could be either marcasite or pyrite. Local concentrations of adularia have been found in matrix cement along with predominant micro-quartz. Opal is not common in breccias, but could have been a precursor to microquartz with jigsaw textures. Assays show that the breccia ores contain substantially more silver than gold, but the silver-gold mineralogy has not been determined.

Large volumes of silicified rock are cut by quartz-sulfide veinlets (fig. 7H) containing small amounts of silver and gold that contribute about 20 percent of the total reserves. The geometry of stockwork ore is well illustrated by relations on the 4040 bench in the Wood pit (fig. 9). The stockwork veins occur in argillized rocks only in rare localities where the argillic alteration locally overprints the earlier silicification. The veinlets generally are a few millimeters wide, spaced several centimeters apart, and are most widespread in silicified rhyolite porphyry. Most stockwork veinlets are associated in time and space with pervasive early silicification, although there also are later cross-cutting veinlets. The lack of stockworks (and significant amounts of silver and gold) in argillized rocks appears to chiefly reflect physical conditions (lack of brittle character).

Supergene Ore

The upper part of the Sleeper deposit has been modified by supergene processes that redistributed gold into uncemented fractures and voids; silver was leached from electrum and redeposited as halide minerals (figs. 8G,H). Naumannite was replaced by gold (low Ag) and cerargyrite (fig. 8G). Electrum in samples from the upper 30 m of the veins typically has rims that are gold-rich (86 wt percent Au, 14 wt percent Ag) and intergrown with cerargyrite (AgCl), and cerargyrite fills late fractures and vugs. Extremely rich samples of gold with moss texture that formed in voids and fractures indicate that gold was mobile at millimeter to meter scales. Kaolinite, halite, and films of Fe-Cl, Fe-SO_4, and Co-oxide minerals fill fractures and vugs. Despite clear evidence for mobilization of silver and gold, bulk Ag/Au ratios (as in blasthole assays) do not change appreciably in the upper, oxidized portion of the ore bodies, and no evidence has been found for an enrichment blanket.

SILICA PETROGRAPHY

The optical character and morphology of silica minerals in various ore and alteration settings can be used to characterize the Sleeper mineralization. There are three varieties of silica at Sleeper which we term quartz, microquartz, and opal. Very little silica at Sleeper has the fibrous structure and mammilary form of chalcedony (Frondel, 1962).

Quartz has normal optical character, is generally clear in transmitted light and mostly free of mineral or other inclusions, and by our definition is coarser than 100 μm. It is clear to milky, and vitreous to the eye or hand lens. It occurs chiefly as phenocrysts, and in some rare coarsely crystalline parts of veins; thick veins more than a few centimeters wide appear to be quartz but most are fine-grained varieties.

Microquartz is microcrystalline quartz that has anhedral to subhedral form and is about 1 to 100 μm in size. Most characteristic of stockwork veinlets and breccia cement (figs. 6D, 7H), microquartz at Sleeper is clear to pale tan in transmitted light, has normal first-order gray-white birefringence, but does not have the sharp extinction of quartz. There are substantial amounts of micron-size included material that probably cause the gray, gray-blue, black or white colors observed in hand specimens. The typical jigsaw texture of interlocking fine grains suggests that the microquartz may have formed by recrystallization of a gel (Lovering, 1972). One variety of microquartz has abundant inclusions, some in growth bands that are chiefly tetragonal or rhombic (fig. 6H); this silica is interpreted to be pseudomorphous after fine calcite.

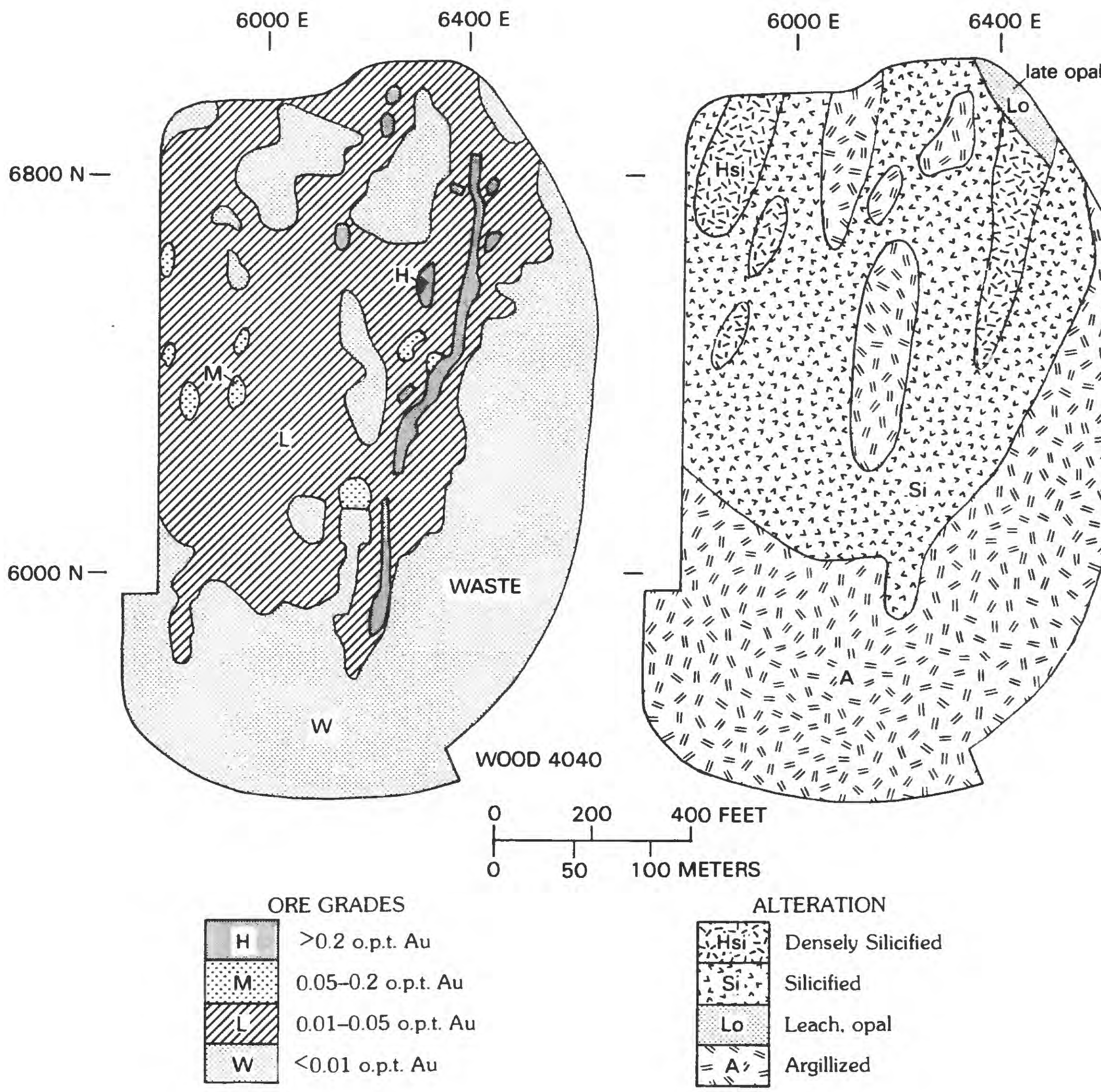

Figure 9. Maps showing distribution of ore and alteration on 4,040 bench of Wood pit. A, Generalized gold distribution based on blasthole assays (4.6 m centers). B, Generalized distribution of alteration in rhyolite porphyry based on mapping of blasted muck.

Opal is cloudy tan, brown, and orange, to nearly opaque in transmitted light, and isotropic to weakly anisotropic (figs. 6D,F; 8A,D). It has numerous irregular tiny inclusions, some of which are opaque (probably iron oxide). Examination at 1,000 X reveals large differences in index of refraction between grains, probably caused by variable water content that has a strong affect on index of refraction in opal (Frondel, 1962). Larger areas of opal have branching syneresis cracks. X-ray diffraction shows that some opal at Sleeper yields only a broad hump near 4Å, and other varieties display variable development of one or two peaks in this region that are attributable to ordering characteristic of crystobalite and termed "opal-C" and "opal CT" (Jones and Segnit, 1971). These ordered forms of opal probably developed by recrystallization after precipitation, as is commonly observed in older sinter layers in hot springs deposits (White and others, 1988). Opal at Sleeper has many colors (white, pale yellow, reddish brown, black), and can be massive with a waxy luster or fine grained and powdery.

Silica in banded high-grade veins is milky white, tan, brownish red, blue-gray, and black, and the colors emphasize the banding. Most of the silica has a low luster on sawn or cleaned surfaces, but in some layers it is vitreous. Some small open cavities are present, but crystal faces are rare. In thin section (figs. 8A,D), the silica consists of interlocked, anhedral grains (jigsaw texture of Lovering, 1972) very fine-grained microquartz . Most grains are in the range of 1 to 20 μm; the coarsest grains are about 100 μm. Unlike quartz, adularia in veins is euhedral; some adularia is relatively coarse (50-200 μm), but most grains are less than 20 μm (fig. 6G). Locally, microquartz replaces a former mineral, probably calcite, and produces a texture resembling travertine (fig. 6H).

Smaller veinlets and breccia cement are chiefly microquartz (fig. 7H) with wide local variations in grain size, grading down to opal. Wider veinlets and some matrix cements have banding similar to that in the larger banded veins. Sparse aluminum minerals occur in these veinlets as adularia, kaolinite, and fine (10-20 μm) alunite (figs. 6D,F).

Silica in altered wall rocks is both opal and microquartz. Plagioclase phenocrysts and groundmass commonly are totally replaced by opal (fig. 6D); scanning electron microscope-energy dispersive system (SEM-EDS) analyses indicate little or no aluminous minerals are left. Or, plagioclase can be replaced by microquartz whereas groundmass is replaced by opal. Vesicles in dacite flows are generally filled by microquartz or microquartz with opal cores. Thin silica veinlets in these altered rocks can be either opal or microquartz.

The very fine grained silica minerals at Sleeper are not suited for trapping fluid inclusions, especially those useful for determinations of temperature and salinity. Most of the fluid inclusions larger than 2 μm are secondary two-phase inclusions in quartz phenocrysts. Many of the tiny fluid inclusions are filled with a single phase, which is suggestive of "low" temperatures of formation. Some heating-stage tests on two-phase inclusions in vein quartz yielded filling temperatures in the range 200-250°C (R.J. Bodnar, unpub. report to AMAX Exploration, 1986; Saunders, unpub. data, 1987). These atypical inclusions and their information may not be pertinent if they reflect recrystallization of opaline silica or a maximum thermal pulse unrelated to ore deposition. The warnings of Sander and Black (1988), that many fluid inclusions in fine-grained silica of epithermal ore deposits can reflect recrystallization and yield erroneous data are especially appropriate for Sleeper.

Silica minerals at Sleeper tend to be much finer grained than in other epithermal volcanic-hosted deposits we have studied in the Western United States; another notable exception is the silica at the Paradise Peak silver-gold deposit (John and others, 1990). The fine-grained varieties of silica in epithermal veins described by Sander and Black (1988) would be at the coarse end of the scale at Sleeper! Textures of vein-filling silica minerals at Sleeper are more like those we have seen in sinter than in veins elsewhere. Further, the rarity of euhedral forms, coarse crystals (>1 mm), and oriented overgrowths--features that are generally indicative of orderly, equilibrium growth--are notably spare or absent at Sleeper. Buchanan (1981) concluded that textures of silica are symptomatic of the environment of formation and that repetitive banding in veins is not easily explained.

ALTERATION

All Tertiary rocks exposed in the pits were moderately to intensely altered during many stages of hydrothermal and supergene alteration. Drilling in the area demonstrates that argillic alteration extends for 500 to 1,500 m beyond known ore (Wood, 1988). Silica-pyrite alteration dominates a broad area from the veins outward for more than 700 m. Silicification and argillic alteration zones are diffuse rather than localized along individual centimeter-scale veins as in classical base-metal veins (Meyer and Hemley, 1967). Four general types of alteration can be distinguished: silicification, argillization, acid leaching, and supergene. The distribution of hydrothermal alteration types is shown on figure 10.

Silicification

Replacement and open-space filling by silica minerals are the most prominent and symptomatic alteration at Sleeper. Early silicification, accompanied by pyrite, resulted in pervasive replacement of plagioclase phenocrysts and groundmass by silica (fig. 6D). Rock textures remain intact despite large chemical changes. Broad zones of rhyolite porphyry were silicified at this stage. This alteration deposited silica in phenocrysts and groundmass that is murky tan in transmitted light and isotropic to weakly anisotropic; these optical properties and many X-ray diffraction patterns suggest the silica is (or was) opal. This early silicification filled vesicles with microcrystalline to opaline silica and peppered pyrite through the groundmass of tuffs and flows. Preliminary macroscopic observations of altered glassy rock cuttings from drill holes west of the pits suggest they underwent similar silica-pyrite alteration. The early silicified rocks have high potassium contents (3-6 wt percent K_2O) and little or no Ca and Na. Sanidine generally survived the early silicification, and sericite formed in dacite flows and tuff units. Traces of Fe-Mg silicate minerals originally in the volcanic rocks were converted to mostly opaque forms of complex mineralogy. Alunite occurs in some early silicified rocks (fig. 6F), but possibly was a later addition. Analyses of hand samples of early silica-pyrite altered rocks generally show <0.1 ppm Au unless veinlets are visible, in which case much higher values can occur.

Silicification of several types accompanied ore stages. Massive white opal as much as 1-meter thick commonly occurs parallel to high-grade veins, generally on the footwall side; this opal fills reopened parts of the veins. Silicification is intense in breccia and stockwork ore zones. Because most, if not all, of this ore-stage silicification seems to be superimposed on

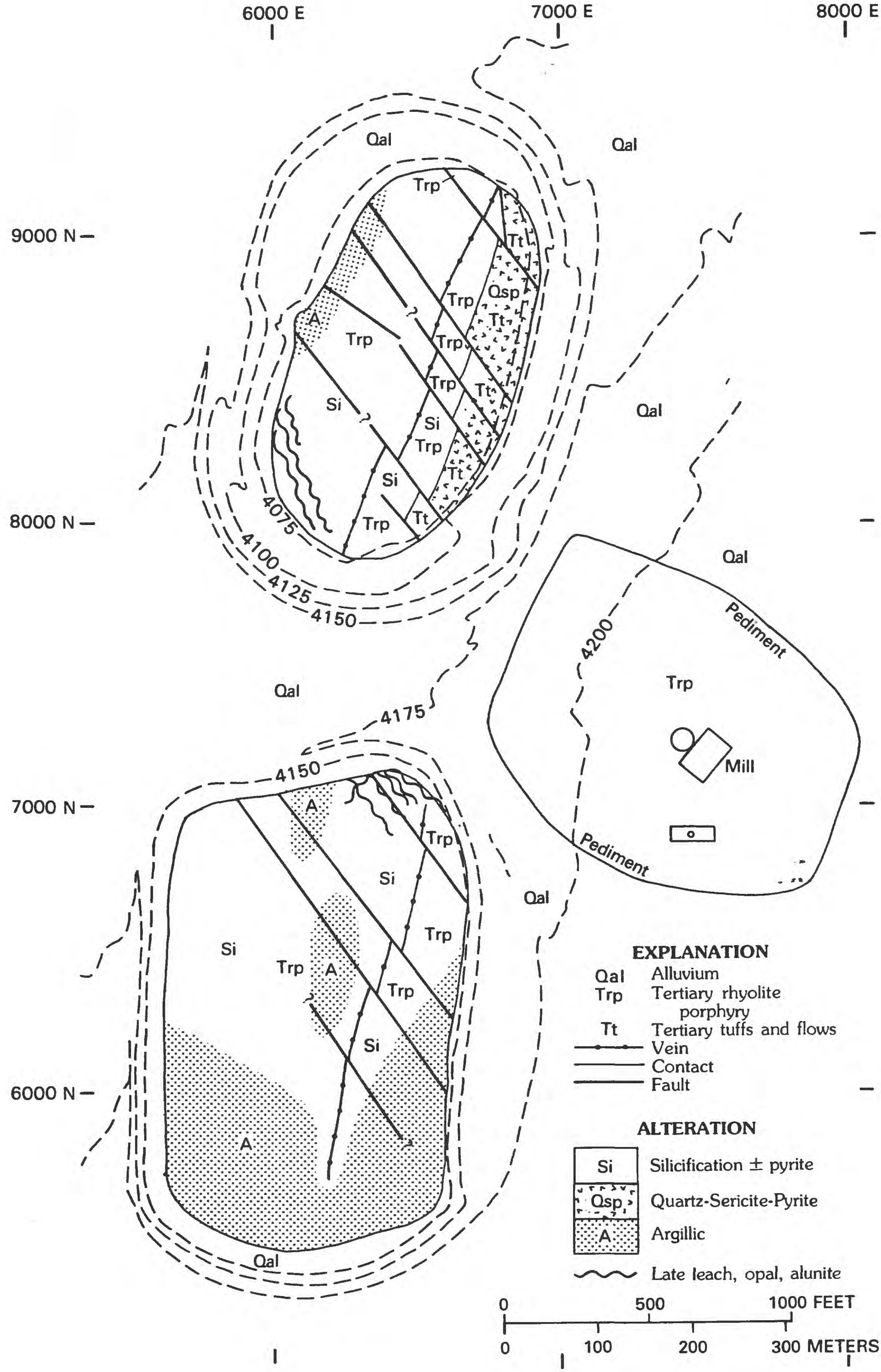

Figure 10. Distribution of hydrothermal alteration in the Sleeper mine. Geologic base is same as figure 4.

previously silicified rocks, effects of just this stage are difficult to estimate.

Late-stage silicification in the form of opal is controlled by post-ore faults and fractures. This multistage alteration is barren (except for earlier gold-silver incorporated in the rocks). This late opal typically contains abundant light-colored alunite, kaolinite, or jarosite. Small amounts of native sulfur are enclosed in the late silica. Some of this opaline silica fills spongelike voids created by acid leaching, and some occurs as fine powdery white opal superimposed on hard dark-gray silica-pyrite alteration. This late alteration is most prominent at the southwest end of the Sleeper pit and the north end of the Wood pit.

Late white powdery fracture coatings are widespread and difficult to characterize while mapping. X-ray diffraction studies show that alunite, kaolinite, and opal or opal-CT are equally common. If there is enough material to test for hardness, then opal can be distinguished from alunite. Massive, hard opal commonly is altered to a fine chalky variety (opal or opal-CT by X-ray diffraction). Thin films (a few microns wide) of alunite or kaolinite line fractures and voids according to SEM-EDS analysis. Generally, it can not be determined if these phases reflect late hot springs deposition or supergene alteration.

Opal has recrystallized to cristobalite at many places, most consistently along the west side of the Sleeper pit (the hanging wall of the Sleeper main vein). Rhyolite porphyry in this zone was altered to opal, but the silica yields X-ray diffraction peaks typical of cristobalite forms "opal-C" and "opal-CT" (Jones and Segnit, 1971). The opal-C and opal-CT probably reflect recrystallization induced by later periods of hydrothermal activity as is well known in modern geothermal systems (Fournier, 1985). Natroalunite also occurs in these rocks.

Argillic Alteration

Feldspar phenocrysts and aphanitic groundmass in barren and low-grade peripheral zones commonly are altered to clay minerals. X-ray diffraction indicates that kaolinite, smectite, and illite ("sericite") are most common. Plagioclase phenocrysts have been replaced by clay minerals and alunite that are so fine grained that normal optical properties cannot be used to distinguish them or to determine relative ages. Sanidine survives most argillic alteration (fig. 6E), but locally is altered to sericite or kaolinite. Groundmass generally is altered to very fine grained silica-clay mixtures. Only SEM-EDS analysis of areas a few microns in diameter permits specific identification. Least altered rocks (footwall samples with narrow pyrite veinlets and slight bleaching) contain chiefly smectite, whereas more conspicuously altered, friable samples generally contain mixtures of kaolinite, smectite, and sericite.

Hypogene argillic alteration occurs peripheral to zones of early silicification; commonly there is a transition zone from 3 to 50-m wide of clay-altered plagioclase in silicified groundmass. Most argillized rocks are so friable that they cannot be studied in thin section; in such rocks the groundmass seems to be mostly hard and siliceous but presence of a few percent of clays is thought to weaken the rock. The broad argillized zones are barren of silver and gold, and contain very little sulfide and no silica veinlets. The barren argillized rocks appear to have escaped intense early silicification, perhaps for lack of fracture permeability, and were argillized at a later time.

Sericite-pyrite-microquartz assemblages (fig. 6E) are included in the broad category of argillic alteration because the sericite cannot be discerned in hand specimen. Petrographic and X-ray diffraction studies to date suggest that sericite is more abundant than smectite or kaolinite adjacent to silicified zones and the sericitic rocks generally contain about 0.01-0.1 oz/ton gold. At Sleeper, as elsewhere (Meyer and Hemley, 1967), sericite-pyrite alteration occurs between adularia-bearing veins and outer kaolinite-bearing rocks and probably reflects intermediate fluid compositions such as moderate K/H ratios and weakly acidic pH.

Acid leaching

Thoroughly leached rocks with sponge-like texture that occur in local zones along post-ore faults were produced by acid leaching. These oxidized, light-colored rocks that contain more than 90 percent SiO_2 were leached of most original constituents. Subsequently, opal, alunite, and jarosite were deposited in the porous rocks. Late powdery silica, described previously, seems to be a variety of acid leach alteration. This alteration resembles in some aspects the acid leach alteration in "acid-sulfate" epithermal systems (Meyer and Hemley, 1967; Hayba and others, 1985) but at Sleeper it was not an ore-associated process. The structural setting and 6-Ma age of the acid leaching at Sleeper suggest it most closely resembles solfataric alteration at very shallow depths in geothermal systems (White and others, 1988; M.L. Silberman, oral commun., 1989).

Supergene alteration

Oxidative alteration effects are widespread in the upper part of the Sleeper orebody. The prominent red coloration of upper pit walls reflects destruction of sulfides and local redistribution of iron into fractures. The interior, protected parts of rocks commonly are partially oxidized to green or pink hues, and pyrite can persist inside silicified rocks. Pyritic tuffs on the east side of the Sleeper pit have been oxidized to tan alunite-jarosite-limonite-bearing mixtures. Feldspars are altered to white clays in downward tapering light-colored streaks that follow open fractures. X-ray diffraction analyses show that these zones are enriched in kaolinite, alunite, and jarosite. Microprobe and SEM-EDS analyses demonstrate that fractures and voids are filled by phases of unusual composition in supergene-altered rocks: some are rich in Cl (as NaCl and AgCl), and many are rich in various combinations of Al, Fe, Mn, and Co as oxides or sulfates. Supergene mineralogy and resultant colors presumably reflect variations in permeability and initial sulfide content (Anderson, 1982).

Broad areas of friable altered rhyolite porphyry in the south and east sides of the Wood pit and the west side of the Sleeper pit may have been affected by supergene alteration superimposed on earlier argillic alteration. Available information suggests that most of the alteration probably was produced during hydrothermal stages.

GEOCHEMISTRY OF HOST ROCKS AND ORES

Geochemical results for major and minor elements (tables 1 and 2) indicate two chief characteristics. 1) Wall rocks show widespread addition of Si, K and S and loss of Ca and Na in several host rock and alteration types. 2) Ores have a simple geochemical suite of Au-Ag-As-Sb-Mo-Se and very low levels of Cu, Pb, and Zn. In high-grade veins, Au is associated only with Ag and Mo. Broadly dispersed As, Se, Cu, Pb, and Zn chiefly reflect pre- or post-ore stages.

Compositions of nearly all volcanic rocks in the pits and foothills have been moderately to highly changed relative to similar glassy rocks in the McDermitt Volcanic field (Rytuba and McKee, 1984); local zones of glassy rhyolite porphyry interecepted in drill holes seem to be little altered, but there are no analytical results for them. Most rocks exposed in the pits have gained Si, K, and S during hydrothermal alteration. Local zones of acid leached rocks are highly depleted in major elements other than Si and Ti. In detail, K is variable , but generally is in the range 3 to 6 wt. percent K_2O and some samples contain 6 to 8 wt percent K_2O. The abundance and variation in K is not a simple expression of alteration character because K resides in many phases: sericite, adularia, alunite, or persistent sanidine. Anomalous amounts of S extend well beyond ore. Most altered rocks contain 1-3 wt percent total S, and many contain more than 5 percent. Lapilli tuffs commonly are very rich in pyrite and contain 10-20 wt percent S. Silica contents are highly variable, from 6 to 97 wt percent SiO_2, but the amounts added or lost are difficult to assess; textural evidence suggests that most rocks have gained 5-25 wt percent SiO_2. Aluminum contents also are highly variable, ranging from less than 1 to 33 wt percent Al_2O_3. Chemical evidence indicates substantial mobility of Al; textures suggest that the scale of movement can be microns to meters. Calcium and Na, originally in feldspars or glass, has been removed (except for Na in sanidine) to very low levels during alteration. Concentrations of 0.5 to 2 wt percent Na_2O in argillized zones seem to reflect later addition of Na as natroalunite.

Some elements, notably Ti, Cr, Nb, Sc, V, Zr, and the rare earth elements (REE), are mostly unchanged by alteration and are thus useful for identifying precursors of highly altered rocks as demonstrated elsewhere (e.g., Pearce and Cann, 1973; Floyd and Winchester, 1978). Most phosphorous concentrations reflect original rock character, but some elevated values in the range 0.6 to 1.9 wt percent P_2O_5 occur in alunite-altered rocks that probably were influenced by supergene processes.

The wide distribution and homogeneity of the rhyolite porphyry unit make it most appropriate for a preliminary analysis of chemical changes in alteration. In this analysis three groups were defined: least altered (but not really fresh; 12 samples), silicified (n=12), and argillized (n=30); highly altered and mineralized rocks were excluded. Examination of the grouped data and application of discriminant function analysis (Davis, 1986) suggest that for most of the 35 major and minor elements the ranges of concentration overlap (no significant differences); however, concentrations of K, Ba, Sr, and Mo are significantly different. Potassium is low in argillized rocks, Ba is highest and Sr lowest in least altered rocks, and Mo is high in argillized rocks. Despite seeming large differences in mineralogy and physical properties, chemical differences are not so large and systematic to be statistically significant for most elements.

A mafic suite of elements (Fe, Ti, P, Cr, V; table 1) is systematically higher in the dacite flows and tuffs compared to rhyolite, and is recognizable despite moderate to intense silicification and argillization. Analyses of drill cuttings show large changes in concentration at lithologic contacts. Several ore-type elements (As, Cu, Ni) are systematically higher in altered dacite flows and tuffs compared with rhyolite porphyry, possibly a reflection of the generally higher iron and pyrite content of the dacitic rocks.

The minor element geochemisty of ore and alteration at Sleeper seems to involve relatively few elements. The ore stages are characterized chiefly by Au, Ag, As, Mo,and Se, whereas non-ore stages are enriched in Sb, Hg, Tl, and Te. Base metals (Cu, Pb, and Zn) are consistently low (table 2). Three generalized geochemical associations are deduced from time and space relations of our analyzed samples: 1) Early silica-pyrite-marcasite alteration produced widespread enrichment in As, Se, Mo, and Fe. These elements, along with Si, K, and S, penetrate large volumes of hanging wall and footwall rocks. 2) Main ore stages including veins, breccia, and stockworks are enriched in Au and Ag but contain relatively low levels of other elements. 3) Post-ore stages produced very erratic and unusual chemical associations in zones of leaching, opal, alunite-jarosite, and earthy iron oxides.

The minor element suite in early silica-sulfide alteration is difficult to define because even a small amount of later veining could contribute values that would bias the bulk determination. The results in the column "altered hanging wall" (table 2) are one estimate. We suspect that the abundant pyrite of this stage carries substantial amounts of As, Se, and other trace elements that create a broad, low-level, signature (fig. 11). The amount of Au and Ag introduced in the early stage is especially difficult to define because later Au-Ag-rich main stage veinlets are likely superimposed; analyses of hand samples lacking veinlets generally contain <0.1 ppm Au, and <4 ppm Ag.

The main ore stage is characterized by very high values of Au and Ag, commonly exceeding those of base metals (table 2). Statistically, only Au and Ag correlate strongly; Au and Mo show a moderate correlation. Lack of correlation between other elements such as Cu, As, and Se with Au or Ag suggest that they were deposited independently. Breccias near the high-grade veins show local enrichments of Mo in the range 50 to 500 ppm.

Late stages of alteration produced extreme chemical variations as a result of leaching and redeposition of oxidized material. The strongest geochemical signature in the pits (other than high grade Au-Ag!) comes from some dark-red to black zones associated with late structures and acid leaching. These atypical zones are rich in Mn, Fe, Co, Ni, Zn, Mo, and P; some contain high concentrations of Ag but little Au. The highest concentrations of many elements occur in this setting: Co in the range 1,000-2,000 ppm, As 1,000-3,000 ppm, and more than 1 wt percent P_2O_5. These elements probably occur as oxidized varieties such as molybdate and arsenate, and Co and Ni are possibly adsorbed on earthy iron-manganese oxide minerals. These deposits could have formed from late thermal springs or from groundwater.

A schematic chemical profile is shown in figure 11. Arsenic values of 100-500 ppm are common in the ore zone. Breccias and stockworks adjacent to the main veins contain relatively less Au (Ag:Au is higher) than in the veins; base metals are about the same. Molybdenum is locally enriched to several hundred ppm in breccias. Recently obtained analyses for Hg, Sb, Te, and Tl show these elements to be highly variable in ore zones. Mercury ranges to more than 50 ppm and typically is about 1 ppm; Sb ranges to more than 7,000 ppm and typically is about 200-800 ppm; Te ranges to more than 20 ppm and typically is less than 0.5 ppm; Tl ranges to more than 100 ppm and typically is 1-5 ppm. Bismuth is generally less than 0.2 ppm, although a few samples contain 1-2 ppm. The suite Sb-Tl±Se±Hg is locally enriched to very high levels, independent of Ag and Au.

The geochemistry of alteration and mineralization in deep drill holes has not yet been studied, but preliminary megascopic observations suggest that base-metal sulfides do not increase significantly. Clay minerals are generally the same as at upper levels; no chlorite is observed.

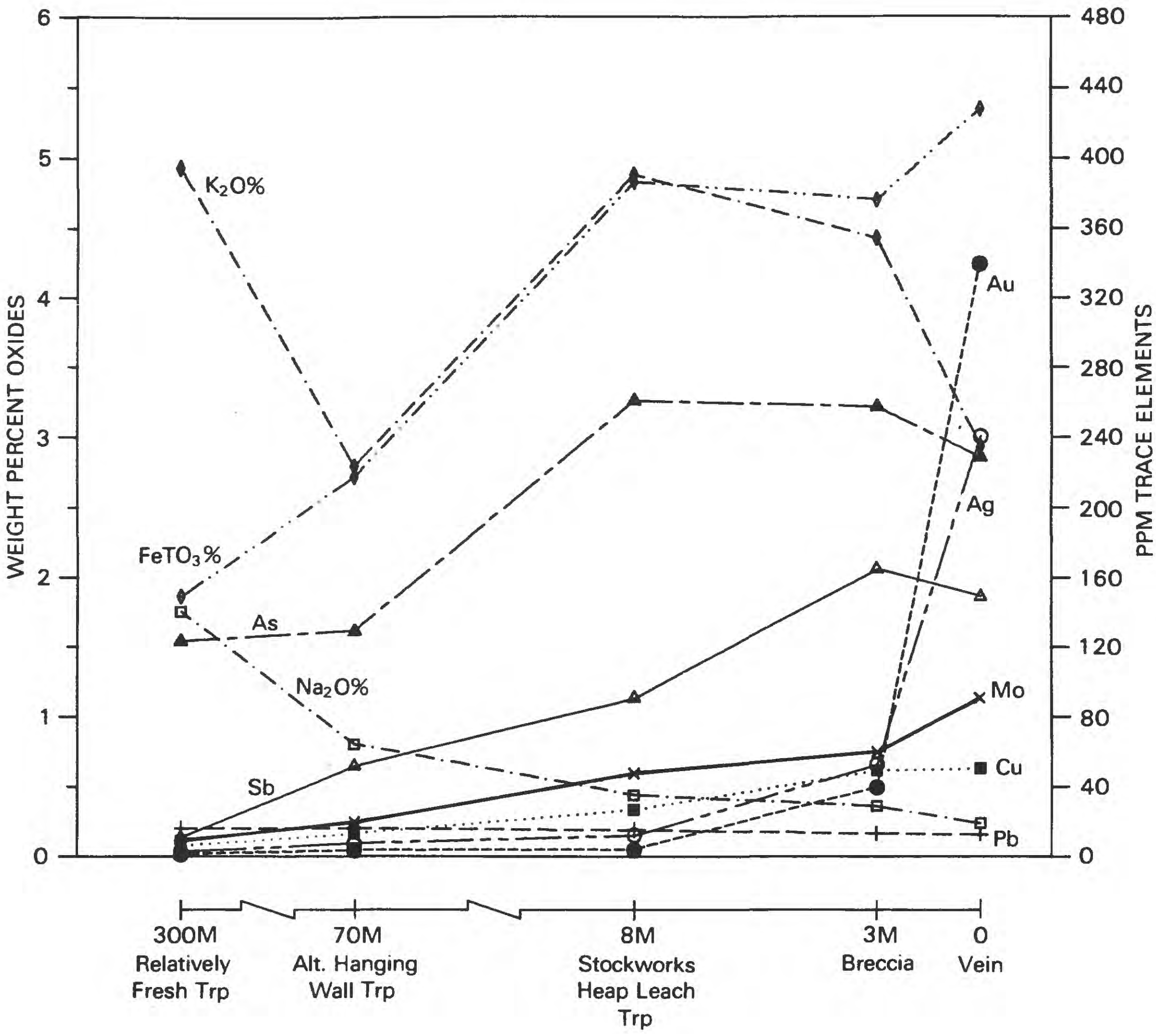

Figure 11. Geochemical zonation of some major and minor elements relative to the Sleeper vein. Data from table 2 is plotted as a schematic section from vein into hanging wall. Major elements in wt. percent, minor elements in parts per million.

DISCUSSION and INTERPRETATION

Physical Environment

The physical setting of deposit formation at Sleeper was clearly shallow, low pressure, and low temperature based on qualitative inferences from mineral assemblages and textures, volcanic features, and similarities to deposits of established setting. Late Tertiary erosion removed a small amount of the deposit. The preserved part of the Sleeper system formed in the depth range of about 50 to 500 m, corresponding to about 5 to 40 bars in a hydrostatic system. Such very low pressures have important implications for many ore-forming processes, ranging from brecciation to mineral precipitation to leaching. Preliminary fluid-inclusion studies on rare inclusions of poorly constrained origin suggest temperatures could have been as high as about 250°C, but mineral textures and probable silicate and sulfide mineral disequilibrium suggest much lower temperatures. The formation and persistence of metastable phases (marcasite and opal) suggests that ore-stage and post-ore temperatures did not exceed about 160°C (Murowchick and Barnes, 1986). The abundant silica in veins and veinlets indicates deposition from liquids because silica is only slightly soluble in low density fluids (vapor phase) (Kennedy, 1950; Fournier, 1985).

Structural Controls

Structure is one of the most important controls on ore formation at district, deposit, and meter scales. Miocene extensional tectonism created the local volcanic field and ore-bearing structures. We suspect that an ancestral fracture zone controlled the emplacement of one or more rhyolite domes and pre-vein silicification. The postulated rhyolite dome complex at Sleeper was important for thermal, chemical, and structural processes.

Brittle rocks were required for ore formation. The majority of the high-grade veins are within the rhyolite dome (or related flows); open tension fractures required for vein deposition favored the massive rock of the dome rather than layered metasedimentary or volcanic rocks. Likewise, stockwork veins and hydrothermal breccias are more widespread in brittle, silicified rocks.

The repeated delicate banding in the high-grade veins suggests relatively stable, quiescent hydrothermal flow in contrast to the hydrothermal eruptions that created breccias and stockworks. Some vein layers are broken, probably by a passive process similar to soft-sediment deformation (perhaps simple gravitational instability) and is seen in opaline veins at McLaughlin, CA (Lehrman, 1986; oral commun., 1988) and other epithermal systems (Bodie, CA and Republic, WA., M.L. Silberman, oral commun., 1989).

Breccia and stockwork structures probably formed during several transient periods of hydraulic fracturing and hydrothermal eruption that contrasted with the quiet times of vein filling. These structures are similar to those observed in modern geothermal systems and several epithermal deposits; fracturing is explained by overpressures caused by vapor phase separation and expansion (Hedenquist and Henley, 1985; Nelson and Giles, 1985). Breccias at Sleeper are vent breccias of clasts that have travelled short distances; eruption craters and fallback breccias could have formed at higher levels. The Sleeper eruptions were local and small as compared with explosive eruptions of volcanic and hydrothermal systems elsewhere (Sillitoe, 1985). Hydrothermal breccias expanded about 20-30 percent (probably upward), whereas stockworks with closely matching angular fragments (jigsaw breccia) expanded less than 10 percent. We suspect that the hydrothermal breccias formed during periods of lithostatic pressure, such as produced by silica sealing (Fournier, 1985; White and others, 1988), whereas vein formed under hydrostatic conditions.

Chemical Environment

The repeated and widespread precipitation of silica, adularia or sericite, pyrite-marcasite, and electrum, and minor amounts of base-metal sulfides is similar to many epithermal quartz-adularia type precious-metal deposits (Hayba and others, 1985; Silberman and Berger, 1985; Heald and others, 1987; Bonham, 1988; Romberger, 1988). Most wall rock alteration at Sleeper involving addition of silica and mobilization of aluminium probably was from slightly acid solutions, whereas vein stages of adularia or calcite were deposited from slightly alkaline (1 or 2 units above neutral pH) solutions (Romberger, 1988). Redox conditions during the main ore stages were moderately oxidizing (approximately equal aqueous sulfide and sulfate), with some incursions of more oxidizing fluids that formed alunite or rare barite. Deposition of adularia and calcite probably was caused by pH increases produced by "boiling" or effervescence of CO_2 (Buchanan, 1981; Romberger, 1988). Such alkaline conditions also would have caused colloidal silica to coagulate (Weres and Tsao, 1981). Boiling produces important changes in fluid chemistry, including oxidation, cooling, loss of HS^-, and increase in alkalinity, any of which would promote deposition of gold (Drummond and Ohmoto, 1985).

Breccias and stockwork veins are compositionally distinct from the banded veins; they have much more pyrite-marcasite, higher Ag:Au ratios, and little or no adularia. Associated alteration suggests that depositional conditions were weakly acidic (Meyer and Hemley, 1967), consistent with the formation of marcasite (Murowchick and Barnes, 1986). The transport of large amounts of iron into breccias and wall rocks required reducing conditions (Barnes, 1979). Fluctuations of the compositions of breccias and stockworks relative to veins indicates major changes in depositional processes or fluid compositions. Mixing of different fluids is one possibility, but isotopic or fluid inclusion evidence for that process is lacking. Alternatively, the fluids depositing FeS_2 and silica in breccias and stockworks might be less evolved than those in the veins; a small amount of boiling and consequent oxidation and loss of H_2S (Drummond and Ohmoto, 1985; Cole and Drummond, 1986) might be sufficient to explain the compositional differences.

The intensity of silicification, chiefly in the form of opal, at the level of bonanza veins is an unusual feature of the Sleeper deposit relative to other quartz-adularia epithermal systems (Hayba and others, 1985; Silberman and Berger, 1985). Judging from published descriptions and our collective experience, the intensity and texture of silica alteration and vein filling in the Sleeper ore zones is more characteristic of highest level zones above bonanza and stockwork ores elsewhere.

SPECULATION

Mineralogical features of the Sleeper ores resemble those of many quartz-adularia epithermal systems and would seem to be explained by models that are popular for this type of deposit (Hayba and others, 1985; Romberger, 1988). Yet these models are overly simplistic for Sleeper; in particular, the models do not explain the extremely high concentrations of gold in the veins or the abundance of opal in veins and wall rocks. Conventional arguments for gold transport, such as by sulfide complexes (Seward, 1984; Romberger, 1988), may be satisfactory for most gold systems, but we suspect that other mechanisms are required to explain both the millimeter scale enrichment of gold in virtually monomineralic layers and the mass of gold in 25-50 m vein shoots. The gold bands and rich ore shoots are more easily explained if concentrations of gold were unusually high in the ore solutions, possibly in the form of colloids. Deposition of gold in the rich bands requires an extremely selective and efficient mechanism that exceeds equilibrium thermodynamic models (e.g., Cole and Drummond, 1986) and does not precipitate other phases. Likewise, opal deposition in veins and wall rocks at Sleeper indicates uncommonly high concentrations of silica in solution, perhaps related to alteration of volcanic glass, boiling, and transport as colloids (Fournier, 1985). Opal deposition at Sleeper and in general suggests the likelihood of kinetic disequilibrium. Replacement of groundmass glass and plagioclase phenocrysts by opal is even more complex than deposition in veins because large amounts of aluminum and other constituents must be removed. A quantitative explanation for the Sleeper veins must explain the distribution and mineralogy of gold and silica and their likely relationship in transport and deposition.

Deposition of gold and silica at Sleeper in banded veins, stockwork veinlets, and breccia matrix may have involved processes comparable to formation of scale in geothermal wells and opal on sinter terraces in modern hot springs. Research on these modern systems (e.g., Rothbaum and others, 1979; Weres and Tsao, 1981; Rimstidt and Cole, 1983) provides insights on mechanisms and kinetics that are pertinent to Sleeper. We propose that three steps were involved. First, the solutions became supersaturated with both silica and gold below the ore zone. Second, boiling and cooling of upwelling fluids created colloids of gold and silica. Finally, deposition occurred where the colloids agglomerated. Monomineralic bands reflect differences in flow velocity, coagulation of colloids, nucleation, and ripening of gels into more ordered and thermodynamically stable forms. Heterogeneous nucleation in supersaturated or colloidal solutions, as observed in the formation of modern sinter and in geothermal scales (Rothbaum and others, 1979; Rimstidt and Cole, 1983), explains many of the gold and silica textures at Sleeper. Ore-associated elements As, Sb, and Se also could have been deposited initially from sols (Joseph-Petit and others, 1973; Renders and Seward, 1989).

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REFERENCES

AMAX Gold Inc., 1989, Annual report 1988: Golden, Colorado, AMAX Gold, Inc., 32 p.

Anderson, J.A., 1982, Characteristics of leached capping and techniques of appraisal, in Titley, S.R., ed., Advances in Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, University of Arizona Press: p. 275-296.

Barnes, H.L., 1979, Solubilities of ore minerals, in Barnes, H.L., ed., Geochemistry of Hydrothermal Ore Deposits, Second Edition: New York, John Wiley, p. 404-460.

Bonham, H.F., Jr., 1988, Models for volcanic-hosted epithermal precious metal deposits, in Schafer, R.W., Cooper, J.J., and Vikre, P.G., eds, Bulk Mineable Precious Metal Deposits of the Western United States: Reno, Geological Society of Nevada, p. 259-271.

Buchanan, L.J., 1981, Precious metal deposits associated with volcanic environments in the southwest, in Dickinson, W.R. and Payne, W.D., eds., Relations of Tectonics to Ore Deposits in the Southern Cordillera: Tucson, Arizona Geological Society Digest, v. 14, p. 237-262.

Burke, D.B., and Silberling, N.J., 1973, The Auld Lang Syne Group, of Late Triassic and Jurassic(?) Age, north-central Nevada: U.S. Geological Survey Bulletin 1394-E, p. E1-E14.

Cole, D.R., and Drummond, S.E., 1986, The effect of transport and boiling on Ag/Au ratios in hydrothermal solutions: a preliminary assessment and possible implications for the formation of epithermal precious-metal ore deposits: Journal of Exploration Geochemistry, v. 25, p. 45-79.

Davis, J.C., 1986, Statistics and Data Analysis in Geology: New York, John Wiley, 646 p.

Drummond, S.E., and Ohmoto, Hiroshi, 1985, Chemical evolution and mineral deposition in boiling hydrothermal solutions: Economic Geology, v. 80, p. 126-147.

Floyd, M.A., and Winchester, J.A., 1978, Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements: Chemical Geology, v. 21, p. 291-306.

Fournier, R.O., 1985, The behavior of silica in hydrothermal solutions, in Berger, B.R., and Bethke, P.M., eds., Geology and Geochemistry of Epithermal Systems: Society of Economic Geologists, Reviews in Economic Geology, v. 2, p. 45-61.

Frondel, Clifford, 1962, The System of Mineralogy, (7th Ed.), vol. III, Silica Minerals: New York, John Wiley, 334 p.

Full, R.P., and Grantham, R.M., 1968, Ore deposits of the Republic mining district, Ferry County, Washington, in Ridge, J.D., ed., Ore Deposits of the United States, 1933-1967: New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 1481-1494.

Hayba, D.O., Bethke, P.M., Heald, Pamela, and Foley, N.K., 1985, Geologic, mineralogic, and geochemical characteristics of volcanic-hosted epithermal precious-metal deposits, in Berger, B.R., and Bethke, P.M., eds., Geology and Geochemistry of Epithermal Systems: Society of Economic Geologists, Reviews in Economic Geology, v. 2, p. 129-167.

Heald, Pamela, Foley, N.K., and Hayba, D.O., 1987, Comparative anatomy of volcanic-hosted epithermal deposits: Acid-sulfate and adularia-sericite types: Economic Geology, v. 82, p. 1-26.

Hedenquist, J.W., and Henley, R.W., 1985, Hydrothermal eruptions in the Waiotapu geothermal system, New Zealand: their origin, associated breccias, and relation to precious metal mineralization: Economic Geology, v. 80, p. 1640-1688.
John, D.A., Nash, J.T., Clark, C.W., and Wulftange, W.H., 1990, Geology, hydrothermal alteration, and mineralization at the Paradise Peak gold-silver-mercury deposit, Nye County, Nevada, in Schafer, R.W. ed, Geology and Ore Deposits of the Great Basin: Reno, Geological Society of Nevada, in press.
Jones, J.B., and Segnit, E.R., 1971, The nature of opal; I. Nomenclature and constituent phases: Journal Geological Society of Australia, v. 18, p. 57-68.
Joseph-Petit, A.M., Dumont, F., and Watillon, A., 1973, Effects of particle size on stability of monodisperse selenium hydrosols: Journal of Colloid and Interface Science, v. 43, p. 649-661.
Kennedy, G.C., 1950, A portion of the system silica-water: Economic Geology, v. 45, p. 629-653.
Lehrman, N.J., 1986, The McLaughlin mine, Napa and Yolo Counties, California: Nevada Bureau of Mines and Geology, Report 41, p. 85-89.
Lovering, T.G., 1972, Jasperoid in the United States--its characteristics, origin, and economic significance: U.S. Geological Survey Professional Paper 710, 164 p.
Meyer, Charles, and Hemley, J.J., 1967, Wall Rock Alteration, in Barnes, H.L., ed., Geochemistry of Hydrothermal Ore Deposits: New York, Holt, Rinehart, and Winston, p. 166-235
Murowchick, J.B., and Barnes, H.L., 1986, Marcasite precipitation from hydrothermal solutions: Geochmica et Cosmochimica Acta, v. 50, p. 2615-2629.
Nash, J.T., 1975, Fluid-inclusion studies of vein, breccia pipe, and replacement ores, northwestern San Juan Mountains, Colorado: Economic Geology, v. 70, p. 1448-1462.
Nelson, C.E., and Giles, D.L., 1985, Hydrothermal eruption mechanisms and hot spring gold deposits: Economic Geology, v. 80, p. 1633-1639.
Pearce, J.A., and Cann, J.R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth and Planetary Science Letters, v. 19, 290-300.
Renders, P.J., and Seward, T.M., 1989, The adsorption of gold(I) complexes by amorphous As_2S_3 and Sb_2S_3 at 25 and 90°C: Geochimica et Cosmochimica Acta, v. 53, p. 255-267.
Rimstidt, J.D., and Cole, D.R., 1983, Geothermal mineralization I: The mechanism of formation of the Beowawe, Nevada, siliceous sinter deposit: American Journal of Science, v. 283, p. 861-875.
Romberger, S.B., 1988, Geochemistry of gold in hydrothermal deposits, in Introduction to Geology and Resources of Gold and Geochemistry of Gold: U.S. Geological Survey Bulletin 1857-A, p. A9-A25.
Ross, C.S., and Smith, R.L., 1961, Ash-flow tuffs: their origin, geologic relations, and identification: U.S. Geological Survey Professional Paper 361, 81 p.
Rothbaum, H.P., Anderton, B.H., Harrison, R.F., Rohde, A.G., and Slatter, A., 1979, Effect of silica polymerization and pH on geothermal scaling: Geothermics, v. 8, p. 1-20.

Rytuba, J.J., 1989a, Volcanism, extensional tectonics, and epithermal mineralization in the northern Basin and Range Province, California, Nevada, Oregon, and Idaho in K.S. Shindler, ed., USGS Research on Mineral Resources, 1989, program and abstracts: U.S. Geological Survey Circular 1035, p. 59-61.

Rytuba, J.J., 1989b, Geology of the volcanic-hosted Sleeper deposit, Humboldt Co., NV.: Geological Society of America Abstracts with Programs , v. 21, p. 138.

Rytuba, J.J., and McKee, E.H. , 1984, Peralkaline ash flow tuffs and calderas of the McDermitt volcanic field, southeast Oregon and north central Nevada: Journal of Geophysical Research, v. 89, no. B10, p. 8616-8628.

Sander, M.V., and Black, J.E., 1988, Crystallization and recrystallization of growth-zoned vein quartz crystals from epithermal systems--implications for fluid inclusion studies: Economic Geology, v. 83, p. 1052-1060.

Saunders, J.A., Utterback, W.C., Day, W.C., and Christian, R.P., 1988, Characteristics of bonanza gold mineralization, Sleeper deposit, Nevada, USA, in Proceedings of Bicentenial Gold '88: Geological Society of Australia, Abstract Series, no. 23, p. 386-388.

Seward, T.M., 1984, The transport and deposition of gold in hydrothermal systems, in Foster, R.P., ed., Gold '82: The Geology, Geochemistry, and Genesis of Gold Deposits: Rotterdam, A.A. Balkema (for Geological Society of Zimbabwe), p. 165-181.

Silberman, M.L., and Berger, B.R., 1985, Relationship of trace-element patterns to alteration and morphology in epithermal precious-metal deposits, in Berger, B.R., and Bethke, P.M., eds., Geology and Geochemistry of Epithermal Systems: Society of Economic Geologists, Reviews in Economic Geology, v. 2, p. 203-232.

Sillitoe, R.H., 1985, Ore-related breccias in volcanoplutonic arcs: Economic Geology, v. 80, p. 1467-1514.

Vikre, P.G., 1985, Precious metal vein systems in the National District, Humboldt County, Nevada: Economic Geology, v. 80, p. 360-393.

Weres, O., and Tsao, L., 1981, Chemistry of silica in Cerro Prieto brines: Geothermics, v. 10, p. 255-276.

White, D.E., Hutchinson, R.A., and Keith, T.E.C., 1988, The geology and remarkable thermal activity of Norris Geyser Basin, Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 1456, 84 p.

Willden, Ronald, 1964, Geology and mineral deposits of Humboldt County, Nevada: Nevada Bureau of Mines and Geology Bulletin 59, 154 p.

Wood, J.D., 1988, Geology of the Sleeper gold deposit, Humboldt County, Nevada, in Schafer, R.W., Cooper, J.J., and Vikre, P.G., eds, Bulk Mineable Precious Metal Deposits of the Western United States: Reno, Geological Society of Nevada, p. 293-302.

Table 1. Chemical analyses of major rock types in Sleeper mine, Humboldt Co., NV

[St dv, standard deviation. Major element oxides in weight percent, normalized for LOI; determined by X-ray fluorescence analysis (D. F. Siems, analyst). $FeTO_3$, total iron reported as Fe_2O_3; LOI, loss on ignition at 900°C. Minor elements in parts per million; determined by induction coupled plasma spectrometry except Zr by energy dispersive X-ray fluorescence (Paul Briggs, analyst).

	Rhyolite porph. least altered n=10		Rhyolite porph. silicified n=7		Rhyolite porph. argillized n=24		Dacite flows silicified n=12		Lapilli tuffs silicified n=11	
	Mean	St dv	Mean	St dv	Mean	St dv	Mean	St dv	Mean	St dv
SiO_2 %	74.3	2.9	81.0	12.4	74.6	13.9	74.8	6.1	74.4	4.3
Al_2O_3 %	14.0	1.7	10.0	6.2	14.4	7.6	18.2	11.8	13.3	4.0
$FeTO_3$ %	1.93	1.0	1.87	1.2	4.01	6.1	3.92	3.6	3.95	1.9
MgO %	0.17	0.07	0.24	0.17	0.40	0.35	0.36	0.15	0.36	0.17
CaO %	0.62	0.77	0.49	0.66	0.54	0.95	0.31	0.11	0.20	0.15
Na_2O %	1.63	0.99	1.87	0.86	1.09	0.91	0.81	0.75	0.60	0.52
K_2O %	5.77	1.45	3.88	3.2	2.82	2.3	5.02	1.0	5.92	1.7
TiO_2 %	0.53	0.09	0.45	0.18	0.86	0.78	1.15	0.52	0.81	0.21
P_2O_5 %	0.12	0.05	0.09	0.04	0.21	0.17	0.23	0.08	0.18	0.08
LOI 900^o %	3.49	1.8	3.24	2.2	9.71	6.5	5.91	1.5	5.72	2.4
Ba ppm	1117.	272.	827.	541.	575.	524.	299.	391.	232.	143.
Ce ppm	61.	12.	55.	24.	55.	32.	49.	19.	38.	19.
Cr ppm	2.6	0.7	7.4	12.	6.9	15.	69.	55.	38.	27.
Mn ppm	126.	143.	185.	135.	20.	19.	38.	21.	1331.	526.
Nb ppm	9.3	4.2	10.	5.	10.	4.	10.	3.	10.	8.
Sc ppm	6.1	1.5	6.2	1.7	7.7	3.3	11.	5.1	7.2	5.3
Sr ppm	138.	42.	128.	53.	247.	261.	283.	182.	349.	600.
Th ppm	12.	1.8	12.	1.5	12.	3.7	4.3	0.6	8.1	2.7
V ppm	18.	4.8	19.	10.	48.	90.	134.	89.	61.	34.
Y ppm	27.	11.	23.	13.	18.	17.	9.8	5.5	16.	13.
Zr ppm	253.	33.	263.	21.	269.	59.	204.	40.	235.	86.

Table 2. Partial chemical analyses of six types of ore and altered host rocks, Sleeper mine, Humboldt Co., NV

[Analyzed samples are hand specimens or drill cuttings (1.5 m interval); TRP, rhyolite porphyry; St dv, standard deviation; --, no data. Major element oxides in weight percent; minor elements in parts per million except Au and Au in oz/ton, determined by induction coupled plasma sspectrometry (Paul Briggs, USGS, analyst) except Au and Ag by fire assay (AMAX Gold, Inc). FeTO3, total iron reported as Fe2O3]

Element	TRP relatively fresh 12 samples		Altered TRP hanging wall 22 cuttings		Heap leach hanging wall 26 cuttings		Breccia ore hanging wall 18 cuttings		Vein ore 19 cuttings		Black breccia hand samples n=16	
	Mean	St dv	Mean	St dv	Mean	St dv	Mean	St dv	Mean	St dv	Mean	St dv
Al2O3 %	12.6	1.39	14.1	6.6	14.5	10.1	9.02	2.44	7.00	3.20	9.02	1.62
FeTO3 %	1.86	1.00	2.72	4.71	4.86	1.96	4.73	2.28	5.86	4.14	3.72	2.15
K2O %	4.94	1.33	2.77	2.05	4.88	1.80	4.46	1.92	2.89	1.56	5.30	5.06
Na2O %	1.75	1.09	0.78	0.87	0.41	0.26	0.40	0.28	0.22	0.20	0.42	0.56
TiO2 %	0.43	0.13	0.50	0.13	0.31	0.08	0.23	0.15	0.22	0.21	0.33	0.13
Ag ppm	2	---	6	5	16	14	55	81	290	359	31	27
As ppm	150	160	129	128	268	150	262	195	239	213	434	296
Ba ppm	1092	253	542	370	227	269	182	118	296	323	342	393
Cu ppm	4.1	1.7	8.4	8	35	15	46	16	49	15	74	81
Mo ppm	9.4	5.4	19	20	53	49	64	45	88	64	95	224
Pb ppm	19	2.6	19	11	17	6.6	17	4.2	15	16	8.4	4.5
Sb ppm	44	36	102	79	148	204	166	229	152	95	82	59
Zn ppm	30	25	43	59	47	62	36	33	44	34	14	12
Au oz/ton	--	--	--	--	0.04	0.03	0.42	1.2	10.	13.3	0.03	0.03
Ag oz/ton	--	--	--	--	0.38	0.33	1.5	2.6	7.	9.6	0.90	0.78