Alteration and Precious Metal Mineralization Associated with The Toquima Caldera Complex, Nye County, Nevada

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Abstract

The Toquima caldera complex consists of three nested and/or overlapping calderas and their eruptive products: dacitic (65.3% SiO_2) to high-silica rhyolitic (78.0% SiO_2) ash-flow tuffs. The calderas range in age from 27.2 to 23.6 Ma, becoming younger and smaller from northwest to southeast. The youngest two of those calderas, Mount Jefferson and Trail Canyon, are associated temporally with four precious metals systems of economic importance that collectively contain at least 8 million oz of gold and 30 million oz of silver. Of the four deposits, the Round Mountain mine is currently producing more than 100,000 oz per year of gold, the Gold Hill and Jefferson Canyon deposits produced gold and silver in the past, and the Corcoran Canyon prospect is the site of promising drill intercepts.

Primary structural controls of mineralization at all the deposits are sets of northwest-striking and northeast-striking faults. In addition to guiding mineralization, those faults may have controlled the rise and eruption of magma to form the calderas and locally reactivated the caldera margins after eruption. The faults are possibly related to the waning stages of pre-basin-range extension (closely spaced faulting and/or diking and associated stratal tilting) that largely predates formation of the complex. The interaction of those faults with volcanism, rather than processes associated strictly with caldera resurgence, likely provided the close temporal link between caldera magmatism and mineralization.

Mineralized outcrops at all the deposits represent paleodepths ranging from a few tens to possibly 1,200 m, based on stratigraphic reconstruction. Precious metal deposition occurred over depth ranges of at least several hundred meters. The range in total depths of mineralization is well within the range of explored depths of active, volcanic-hosted geothermal systems.

Some aspects of geological variability among the deposits correlate with inferred paleodepths of formation. The shallower deposits— Gold Hill and Round Mountain— are not associated at present levels of exposure in outcrop or drill intercepts with intrusions that could have served as heat sources for the hydrothermal systems. The intermediate and deeper deposits— Corcoran Canyon and Jefferson Canyon— are associated with outcropping, altered, silicic intrusions, some of which intrude mineralized faults. Round Mountain and Gold Hill have higher gold:silver ratios relative to Corcoran Canyon and Jefferson Canyon.

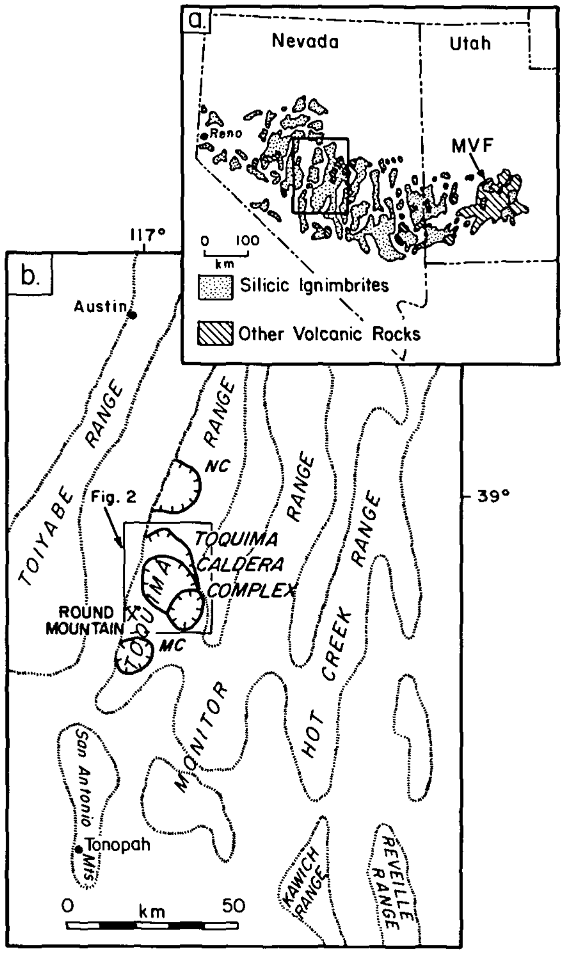


FIG. 1. *Location of the Toquima caldera complex within a. the west-northwest-trending belt of 34 to 17* volcanic rocks (MVF—Marysvale volcanic field), and b. the Toquima Range (NC—Northumberland caldera (McKee, 1974); MC- Manhattan caldera (Shawe, 1981a)).

Alteration at all the deposits consists of early, propylitic alteration overprinted by later bleaching, and by latest, high-level silicification. Detailed study at Round Mountain and reconnaissance at Jefferson Canyon indicate that early, hydrothermal feldspars replacing magmatic minerals are largely preserved through later overprints that changed the megascopic appearance of host rocks. Therefore, the hydrothermal feldspars are useful for tracing the distribution and intensity of early, ore-related alteration.

Propylitic alteration is characterized by K-feldspar (Ksp(I)) replacing magmatic sanidine phenocrysts and albite (alb) replacing plagioclase phenocrysts. Intensity of this alteration can be estimated in thin section by percent replacement of sanidine by Ksp(I). Other minerals in the Ksp(I)-alb association include chlorite (after biotite), calcite, pyrite and locally epidote and illite.

Some of the later bleaching consists of alteration of chlorite to mixed-layer clays or white mica, preserving the Ksp(1)-alb feldspar association. Much bleaching, however is associated with K-feldspar replacing previously albitized plagioclase phenocrysts (Ksp(II) alteration). Magmatic sanidine phenocrysts (or Ksp(I) pseudomorphs of sanidine) are preserved, and previously chloritized biotite phenocrysts are altered to white mica. Intensity of this potassic alteration can be estimated in thin section by percent replacement of plagioclase by Ksp(II).

At Round Mountain, bulk-minable gold mineralization occurs where pervasive, 100 percent Ksp(I)-alb (intense propylitic) alteration is cut by quartz-adularia-pyrite veins in densely welded tuff and where pervasive, 100 percent Ksp(I)-alb alteration is overlapped by pervasive, Ksp(II) (intense potassic) alteration in poorly welded tuff. Ksp(II) alteration does not contain bulk-minable gold mineralization where it overprints rock not previously altered to 100 percent Ksp(I)-alb. At Jefferson Canyon, potentially bulk-minable silver mineralization is hosted by Ksp(II) alteration superimposed on 100 percent Ksp(I)-alb alteration.

Introduction

Late Oligocene to Miocene ash-flow tuffs of the Toquima caldera complex of central Nevada (Fig. 1) host three precious metals deposits of current or historical importance and one of likely future significance. These deposits collectively have produced over 2.4 million oz of gold and silver; they contain 8 million oz of gold and 30 million oz of silver as reserves. The Round Mountain mine is presently active, the Jefferson Canyon and Gold Hill deposits were mined in the past, and the Corcoran Canyon prospect is at an early stage of development drilling.

Over the past 10 to 15 years, the area of the Toquima caldera complex has been the subject of numerous studies that concentrated individually on its regional geology, volcanic geology, and ore deposits. This report represents a first effort to use those studies to compare and contrast the several deposits within their volcanic and structural settings. In particular, the Toquima caldera complex and its contained ore deposits provide another opportunity to evaluate the degree to which volcanic-hosted precious metals deposits may be intimately related to the caldera cycle, as proposed by Smith and Bailey (1968).

Previous Work

The geology and ore deposits of northern Nye County are described in county reports (Kral, 1951; Kleinhampl and Ziony, 1984, 1985). McKee (1974) and Shawe (1981a), respectively, mapped the Northumberland caldera to the north and the Manhattan caldera to the south of the Toquima caldera complex (Fig. 1). Ferguson and Cathcart (1954) and Shawe (1981b) published aerial geologic maps of the Round Mountain quadrangle, which encompass part of the area of the complex. Boden (1986) concentrated on the Toquima caldera complex itself, working out its eruptive history and structural development.

Early reports on historical mining districts of the Toquima caldera complex include Packard (1907, 1908), Loftus (1909), Ransome (1909), and Ferguson (1921). They are summarized and augmented by Kral (1951), Kleinhampl and Ziony (1984), and Tingley and Berger (1985). The Round Mountain Mine, the only one of the deposits being mined today, has been the subject of more recent research, reported by Mills (1984), Sander and Mills (1984), Tingley and Berger (1985), Berger and others (1986), and Sander (1987). Trace element geochemistry associated with mineralization in the complex is reported by Shawe (1977b) and Tingley and Berger (1985).

Regional Geologic Setting

The Toquima caldera complex lies within a west-northwest-trending belt of 34 to 17 Ma volcanic rocks that extends across the Basin and Range province (Fig. 1). These volcanic rocks, mostly silicic ash-flow tuffs, are cut by multiple generations of normal faults that have been divided into two major styles of extension— earlier "pre-basin-range" and later "basin-range" (Zoback and others, 1981).

The term "basin-range" refers to the style of extension that is characterized by widely spaced, moderately to steeply dipping normal faults that produced the prominent corrugated topography of the present elongate basins and ranges and produced only gentle tilting of strata in the uplifted blocks. This style generally is contemporaneous with basaltic and bimodal basaltic-rhyolitic volcanism, low inferred strain rates, and a deep inferred ductile-brittle transition zone (Zoback and others, 1981).

In contrast, the term "pre-basin-range" (Zoback and others, 1981), exemplified by descriptions of the Yerington district (Proffett, 1977) and east-central Nevada (Gans and Miller, 1983; Miller and others, 1983), refers to the style of extension that is characterized by closely spaced, strongly rotated normal faults and strongly tilted strata. Pre-basin-range extension generally is contemporaneous with calc-alkaline magmatism, high inferred strain rates, and a shallow inferred ductile-brittle transition zone (Zoback and others, 1981). In addition to low-angle normal faults, extended terranes are distinguished by strike-slip faults that represent the lateral terminations of individual shovel-shaped normal faults (Proffett, 1977; Gans, 1982) and tear faults that bound regions undergoing differential extension (Gans and others, 1986).

The age of transition from pre-basin-range to basin-range extension varies from place to place within the Great Basin, and probably was not abrupt. In some parts of the Great Basin, pre-basin-range extension began as early as 36 Ma (e.g., Gans, 1982); and later basin-range faulting developed largely within the last 10 Ma (Zoback and others, 1981).

Oligocene to Miocene volcanic rocks within the Basin and Range province host numerous precious metals deposits. The largest of the deposits—Round Mountain in the Toquima caldera complex, Tonopah, Comstock and Goldfield—are giants among the class of epithermal deposits. As a group, volcanic-hosted deposits of the Basin and Range province vary widely in age, volcanic and structural settings, and character of alteration and mineralization. Information summarized here, on the other hand, demonstrates relative similarity among deposits of the Toquima caldera complex.

The Toquima Caldera Complex

Introduction

Eight major volcanic units, ranging in age from 32 to 22 Ma, are exposed in and around the Toquima caldera complex (Table 1; Fig. 2). They unconformably overlie deformed Paleozoic sedimentary rocks and their metamorphosed equivalents, Late Cretaceous granitic rocks of the Shoshone pluton, and a 37-34-Ma-old, north-northeast-striking dike swarm and granodioritic stock located east of Round Mountain (Shawe and others, 1986). Of the eight volcanic units, three, ranging in age from 27.2 to 23.6 Ma, were erupted from the Toquima caldera complex. The others, both older and younger, were erupted from sources outside the complex. Boden (1986) discusses the volcanic and structural development of the Toquima caldera complex in detail; his discussion is summarized here.

Volcanic geology

The Toquima caldera complex consists of three nested and partially overlapping collapse structures— the Moores Creek, Mount Jefferson, and Trail Canyon calderas (Table 1, Figs. 2 and 3). Ages and sizes of the calderas decrease from northwest to southeast. Eruptive products of the complex consist of variably welded, crystal-rich ash-flow tuffs that range in composition from dacite (65.3% SiO_2) to high-silica rhyolite (78.0% SiO_2). Plagioclase, sanidine, quartz, and biotite phenocrysts constitute 10 to 40 percent of those tuffs. Their abundance varies in concert with variable major element compositions of the units; less silicic units contain more plagioclase and biotite, but less sanidine and quartz than more silicic units. Also, less silicic units contain minor hornblende and pyroxene phenocrysts.

Lavas and ashfall tuffs are scarce in the complex, whereas pre- and postcaldera volcanic rocks of intermediate to mafic composition are lacking entirely. Calderas of the complex underwent only limited postcollapse resurgence, although more recent basin-range block faulting has led to differential uplift of portions of the complex.

The Moores Creek caldera formed 27.2 ± 0.6 Ma upon eruption of the high-silica rhyolite (76-78% SiO_2) tuff of Moores Creek. The Moores Creek caldera is the oldest and least well preserved of the three calderas in the complex. Its northern part is well-exposed, but its eastern and western margins are faulted below valley fill, and its southern part is obscured by the later Mount Jefferson and Trail Canyon calderas. The northern margin is defined by an arcuate zone of strongly brecciated Paleozoic sedimentary rocks, by large blocks of Paleozoic rocks and older Tertiary volcanic rocks entrained in the tuff of Moores Creek and by an intrusion of porphyritic, flow-layered rhyolite dated at 26.5 ± 0.7 Ma.

Eruption of the tuff of Mount Jefferson (26.4 ± 0.5 Ma) formed the Mount Jefferson caldera (Table 1, Figs. 2 and 3). Margins of the caldera are marked by tongues of caldera-collapse breccia and by several small aphyric to porphyritic plugs. Field, textural, and mineralogic relations indicate that some of those plugs represent lava-choked ignimbrite-

Table 1.

Volcanic rocks exposed in and around the Toquima caldera complex (K-Ar ages and volcanic sources from Boden, 1986).

Rock Unit	K-Ar Age (Ma)	Source	Alteration and Mineralization
Tuffs of Road Canyon	22.1 ± 0.3 to 23.6 ± 0.4	Unknown, outside complex	Barren
Tuff of Trail Canyon	23.6 ± 0.4	Trail Canyon caldera	Corcoran Canyon
Tuff of Ryecroft Canyon	25.0 ± 0.5	Unknown, outside complex	Barren
Tuff of Mount Jefferson	26.4 ± 0.5	Mount Jefferson caldera	Jefferson Canyon Gold Hill, Moores Creek, Round Mountain
Tuff of Round Mountain (extracaldera equivalent)	26.7 ± 0.6		
Tuff of Moores Creek	27.2 ± 0.6	Moores Creek caldera	Barren
Tuff of Corcoran Canyon	27.7 ± 0.7	Unknown, outside complex (to east?)	Corcoran Canyon
Tuff of Logan Spring	29.6 ± 0.6	Unknown, outside complex	Barren
Megabreccia of Dry Canyon	32.3 ± 0.7	Older than complex; source partially buried by tuff of Round Mountain and alluvium of Big Smoky Valley	Round Mountain

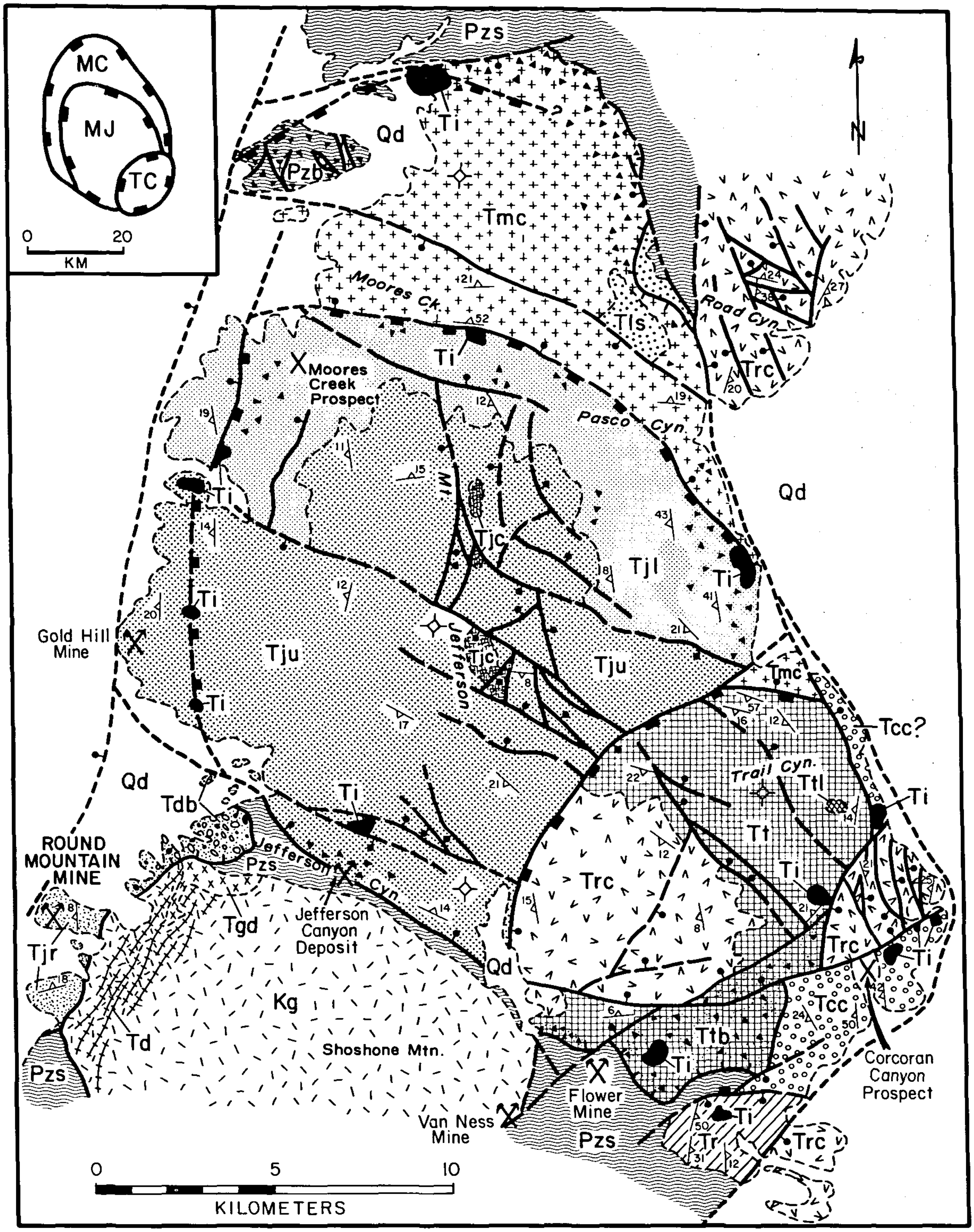
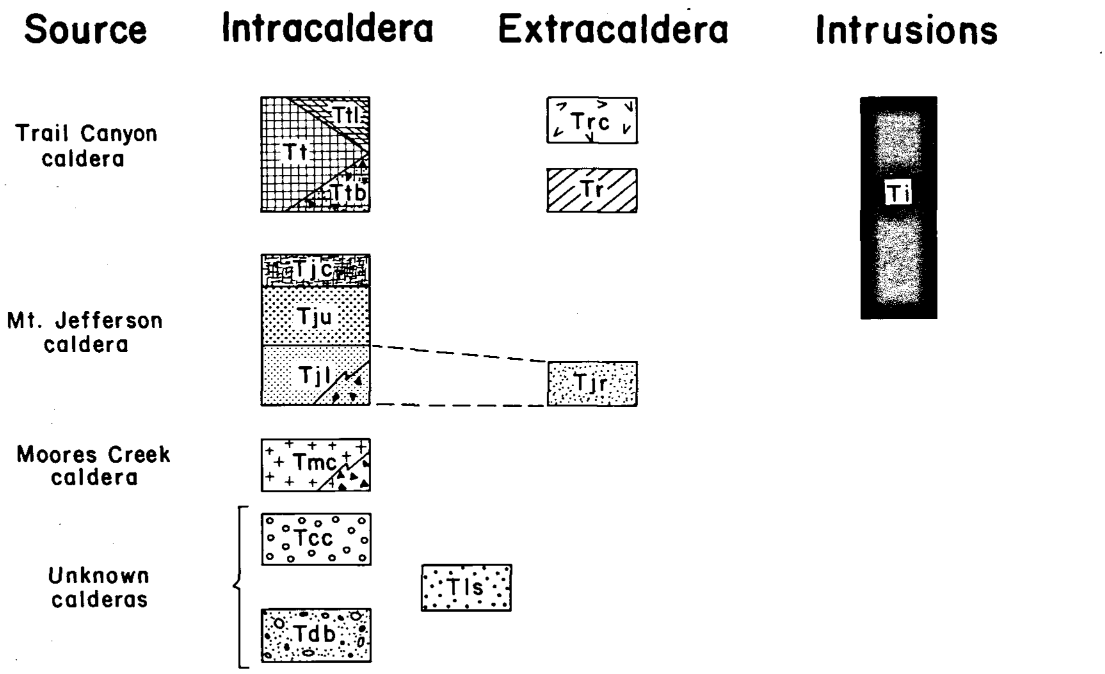


FIG.2. Generalized geologic map of the Toquima caldera complex, with locations of altered and mineralized areas discussed in the text (modified after Boden, 1986). Inset shows generalized boundaries of the calderas before deformation by block faulting. (MC—Moores Creek caldera; MJ—Mount Jefferson caldera; TC—Trail Canyon caldera).



Qd	Alluvium, Colluvium, and Fanglomerate
Trc	tuffs of Road Canyon (23 - 22 Ma)
Ttl / Tt / Ttb	tuff of Trail Canyon (23.6 Ma) Ttl - *local capping porphyritic lava* Tt - upper and lower members, undifferentiated Ttb - caldera collapse breccia
Tr	tuff of Ryecroft Canyon (25.0 Ma)
Tjc / Tju / Tjl / Tjr	tuff of Mt. Jefferson (26.4 Ma) Tjc - discontinuous capping cooling units Tju - upper member Tjl - lower member with lenses of collapse breccia Tjr - outflow Round Mountain member (26.7 Ma)
Tmc	tuffs of Moores Creek (27.2 Ma) with lenses of collapse breccia along margin
Tcc	tuff of Corcoran Canyon (27.7 Ma)
Tls	tuff of Logan Spring (29.6 Ma)
Tdb	megabreccia of Dry Canyon (32.3 Ma)

Ti	Porphyritic to aphyric plugs and lava-choked ignimbrite feeder vents
Tgd	Granodioritic stock (37.4 Ma; Shawe et al, 1986)
	Andesitic to rhyolitic dikes (34 - 37 Ma; *Shawe et al, 1986*)
Kg	Granitic rocks of Shoshone Mountain
Pzs / Pzb	Pzs - lower Paleozoic sedimentary rocks Pzb - severely brecciated Paleozoic rocks and megabreccia
	Contact
	Fault: ball on downdropped side; dashed where approximately located
	Cauldron boundary: ball on downthrown side of margins reactivated by basin-range faulting: rectangle on caldera side.
20	Strike and dip of foliation
	Horizontal eutaxitic foliation
	Mining district or Au - Ag deposit
X	Au - Ag prospect
	Topographic wall of calder[illegible]

feeder vents (Boden, in prep.). The tuff of Mount Jefferson consists of two intracaldera members—lower moderately to densely welded and upper densely welded—and an outflow member informally called the tuff of Round Mountain. The contact between the intracaldera lower and upper members is discontinuously marked by tuffaceous sedimentary rocks. Similar

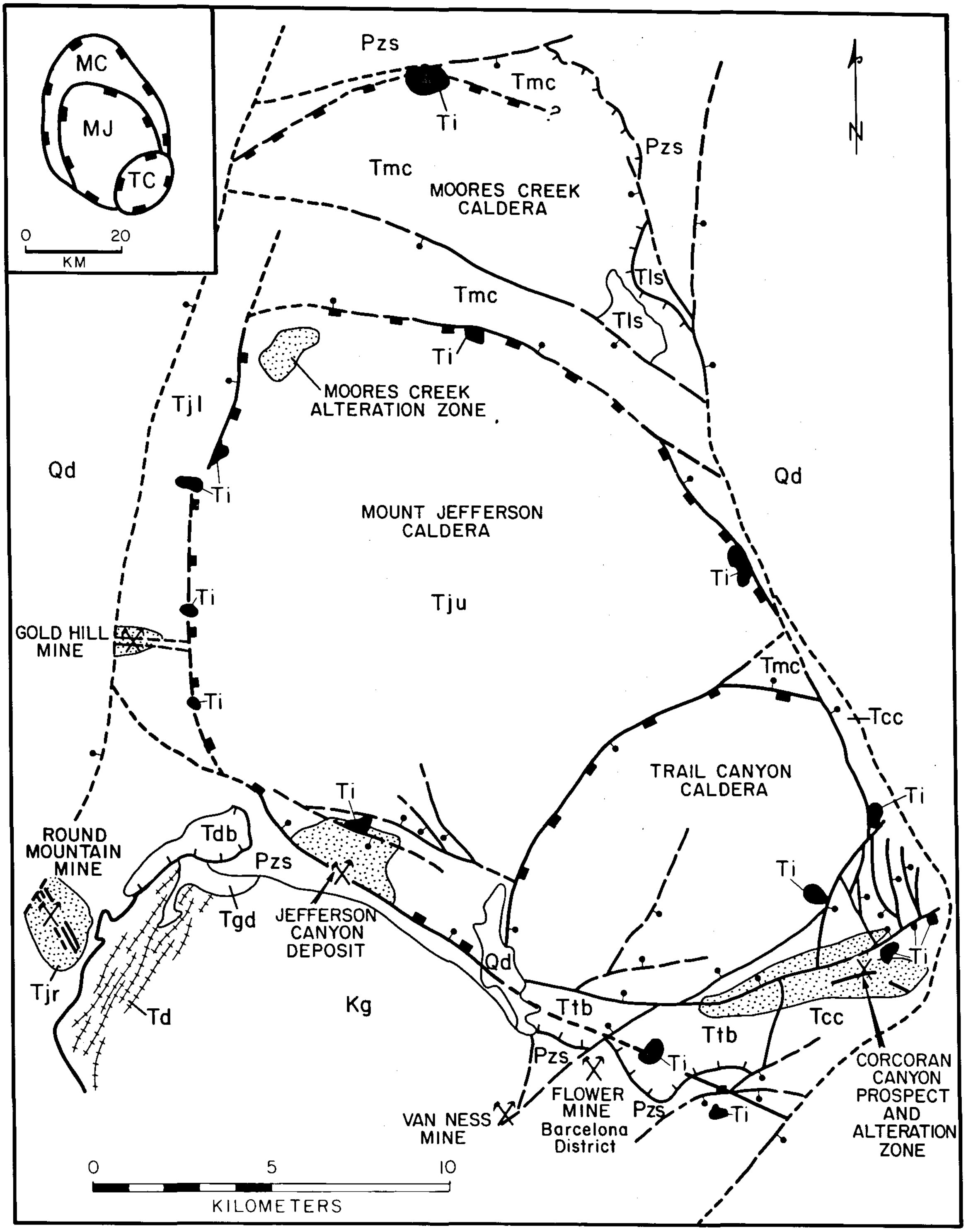


FIG.3. Simplified map of the Toquima caldera complex emphasizing major faults,volcanic structures and alteration (modified after Boden, 1986).

tuffaceous sedimentary rocks occur at the Gold Hill Mine and capped the tuff on top of Round Mountain before being removed by mining. All three occurrences occupy similar stratigraphic positions and could be coeval. Those at Gold Hill and Round Mountain are cut by gold-bearing veins.

The tuff of Round Mountain is zoned from lower, crystal-poor, high-silica rhyolite (77.5% SiO_2), to upper, crystal-rich rhyolite (73.8% SiO_2). This zoning trend is partly overlapped and extended to less silicic compositions in the intracaldera members of the tuff of Mount Jefferson, from 75.7 to 73.3 percent SiO_2 in the lower member and from 73.8 to 67.7 percent SiO_2 in the upper member.

The youngest, smallest, and southeasternmost of the calderas of the Toquima complex is the Trail Canyon caldera (Table 1, Figs. 2 and 3). It formed with the eruption of the tuff of Trail Canyon (70.4-75.9% SiO_2) at 23.6 ± 0.4 Ma. Margins of the Trail Canyon caldera, like margins of the other calderas at the complex, are outlined by collapse breccia and small, porphyritic plugs.

Structural setting

Ash-flow tuffs erupted from the Toquima caldera complex have not been tilted significantly by the pre-basin-range style of extension that occurred in other parts of the Great Basin (Proffett, 1977; Gans and Miller, 1983). However, there is evidence of two periods of extension predating eruption of the complex. The earlier extension was northwest-directed and occurred at 34-38 Ma. The most important evidence of the earlier extension includes the northwest-striking sheeted dike swarm 2 to 3 km east of Round Mountain, mapped by Shawe (1977a, 1981b; Fig. 2) and dated by Marvin and others (1973) and Shawe and others (1986) from 34.4 ± 1.2 to 37.4 ± 2.3 Ma. Deformation associated with that event should consist of northeast-striking normal faults and northwest-striking tear faults that bound structurally tilted domains. Recognition of this deformation is complicated by widespread younger volcanic cover and by the fact that the rocks affected are either relatively homogeneous plutonic rocks or Paleozoic rocks that already were deformed.

The second period of extension is suggested by 30° to 50° southwest tilts of the tuff of Corcoran Canyon (Fig. 2). Cessation of this tilting is well constrained between the age of the tilted tuff of Corcoran Canyon (27.7 Ma) and the age of the overlying, untilted tuff of Trail Canyon (23.6 Ma). Whereas the 34 to 37 Ma extension was northwest directed, the younger event was northeast-directed, as suggested by the orientation of tilting. The major northeast-striking fault that truncates the tuff of Corcoran Canyon and bounds the southeastern margin of the Trail Canyon caldera may represent an oblique-slip tear fault associated with the younger extension.

Although extension (and related tilting) due to both events was essentially complete by the time of eruption of the Toquima caldera complex, northwest- and northeast-striking faults do cut ash-flow tuffs of the complex. They are especially prominent near inferred margins of the calderas (Figs. 2 and 3). At Round Mountain, the northwest faults cutting the tuff of Round Mountain are oblique-slip and of small net displacement (a few to many tens of meters; Sander, 1987). Elsewhere, little evidence of the sense or amount of displacement exists, although relations are compatible with at least some oblique-slip displacement on the northeast-striking Corcoran Canyon fault. Thus, minor deformation associated with pre-basin-range extension continued after eruption of the complex. The waning stages of this deformation were insufficient to noticeably tilt the tuffs of the complex, but did create fractures that guided most of the alteration and mineralization in the area.

Beginning in the late Tertiary, north to northeast-striking block faulting affected central Nevada, segmenting the region into a series of bold ranges and deep, alluviated valleys. At the Toquima caldera complex, this basin-range faulting truncated parts of the complex, locally reactivated original caldera structures, and offset mineralization. One of the most notable effects of the deformation was the uplift and gentle westward tilting (less than 25°) of the intracaldera members of the tuff of Mount Jefferson to form the present, high-standing massif.

Precious Metals Deposits of the Toquima Caldera Complex

Introduction

Of the three calderas of the Toquima caldera complex, the Mount Jefferson and Trail Canyon are associated in time and space with alteration and mineralization, whereas the Moores Creek is not associated with known mineralization. Host rocks for Tertiary mineralization include pre-Tertiary basement rocks, which also host Mesozoic mineralization associated with the granitic batholith (Shawe and others, 1986); ash-flow tuffs older than the complex; and tuffs erupted from the complex. Ash-flow tuffs younger than the complex (tuffs of Road Canyon), erupted from sources outside the area, are barren, even where they occur near older, mineralized tuff (Tables 1 and 3).

Important deposits associated with the complex include the Round Mountain Mine, currently producing more than 100,000 oz of gold per year, the Gold Hill and Jefferson Canyon Mines of recorded historical production, and the Corcoran Canyon prospect of likely future significance. In addition, alteration and weak mineralization in the Moores Creek area and mercury mineralization in Paleozoic rocks of the Barcelona district (Figs. 2 and 3) may be related to the complex. Tables 2, 3, and 4 summarize economic and geologic parameters of the deposits.

The Round Mountain Mine

The Round Mountain Mine contained at least 8.9 million oz of gold and 15 million oz of silver before mining (Table 2). Of these totals, about 1.1 million oz of gold and 0.5 million oz of silver were contained in placers eroded from Round Mountain itself. Host for most of the known mineralization is the extracaldera Round Mountain member of the tuff of Mount Jefferson. Additional mineralization is contained within the megabreccia of Dry Canyon, the Cretaceous Shoshone pluton, and deformed and locally metamorphosed Paleozoic rocks. K-Ar ages of ore-related alteration, 25.1 ± 0.8 to 26.6 ± 0.6 Ma (Silberman and others, 1975; Tingley and Berger, 1985; Sander, 1987) are nearly indistinguishable from the age of the host tuff of Round Mountain.

The tuff of Round Mountain consists of an outcropping, central densely welded portion and a subcropping, lower poorly welded portion (Fig. 4). Before mining, an upper poorly welded portion and overlying tuffaceous sedimentary rocks capped the section on top of Round Mountain itself. Although largely barren of gold, those upper units have been stripped away by recent mining.

The tuff of Round Mountain consists of an outcropping, central densely welded portion and a subcropping, lower poorly welded portion (Fig. 4). Before mining, an upper poorly welded portion and overlying tuffaceous sedimentary rocks capped the section on top of Round Mountain itself. Although largely barren of gold, those upper units have been stripped away by recent mining.

The primary spatial control of mineralization at the mine is a set of northwest-striking, steeply dipping, oblique-slip faults and subparallel joints (Fig. 4) 6 km outside and southwest of the margin of the Mount Jefferson caldera. Data from drilling suggests that some faults pass down into prevolcanic basement along paleoscarps developed in the unconformity (Sander, 1987). The "breccia pipe" that figured so prominently in general older accounts of the mine (e.g. Mills, 1984; Sander and Mills, 1984; Tingley and Berger, 1985; and Berger and others, 1986) has proven in recent mine exposures to consist of coarse sedimentary rocks

Table 2.

Production and reserve data for deposits associated with the Toquima caldera complex.

District	Conatined Pre-1986 Production	Metals Reserves
Round Mountain	Lode[2,4,5] 1,004,000 oz Au ~576,000 oz Au Placer[2] 208,000 oz Au ~100,000 oz Au	Lode[2] 6,833,000 oz Au ~14,000,000 oz Au 175,200,000 tons ore Placer[2] 900,000 oz Au ~450,000 oz Au 30,000,000 tons
Jefferson Canyon	1,000 oz Au[1,5] 300,000 oz Au[1,5] 1 ton Sb[3]	73,000 oz Au[1] 15,466,0000 oz Au[1] 10,450,000 tons ore[1]
Gold Hill	19,000 oz Au[1,4,5] 185,000 oz Au[1,4,5]	NA
Corcoran Canyon	none	Announced high grade Au-Ag intercepts; no reserve data available[1]
Barcelona (Flower and Van Ness Mines)	1,000 fl Hg[3] (Other mines in district recorded production of Au, Ag, Pb)	NA
Moores Creek	negligible	NA

References by footnote for Tables 2, 3, and 4:
[1] CR Exploration Co., unpub. data;
[2] Round Mountain mine, unpub. data;
[3] Kleinhampl and Ziony (1984),
[4] Tingley and Berger (1985);
[5] Kral (1951);
[6]Boden (1986);
[7] Sander (1987);
[8] Ervine (1972);
[9] Silberman and others (1975),
[10] Shawne and others (1986);
[11] Boden, unpub. data,
[12] Naeser and others (1980).

Table 3.

Volcanic and structural setting of deposits associated with the Toquima caldera complex.

District	Major Host Rock (Age, Ma)	Age of Mineralization (Ma)	Spatial Relation to Caldera	Spatial Relation to Nearby Intrusions	Geometry of Mineralization	Inferred Paleodepth of Mineralization (m)	Depth Range of Mineralization (m)
Round Mountain	Tuff of Round Mountain (26.7 ± 0.6; early outflow of Mt. Jefferson caldera[6]); also older Tert. volcanic, Cret. plutonic, and Pz. sedimentary rocks	25.1 ± 0.8 to 26.6 ± 0.6 (K-Ar on alteration minerals) [4,7,9,10]	Outside and 6 km SW of Mt. Jefferson calders; may lie over buried margin of 32.3 Ma caldera	No intrusions encountered to depth of drilling (about 1 km)	NW, steeply dipping, oblique-slip faults and related joints control sheeted veins in outcropping densely welded tuff; veins and stratabound disseminations in subcropping poorly welded tuff[2,3,4,7]	A few ten to hundreds of m (unknown thickness of volcanclastic sedimentary rocks capping tuff of Round Mtn.; probably no major covering ash flow	At least 750
Jefferson Canyon	Tuff of Mt. Jefferson (26.4 ± 0.5[6]); astride contact of upper and lower members	25.9 ± 1.1 (inferred from fission track age on zircon from altered intrusion)[10,12]	On topographic margin of Mt. Jefferson caldera where reactivated by major NW fault	Altered rhyolite dikes and stocks crop out in mineralized area, partially controlled by NW fault	Closely spaced veins sub-parallel to, and in hangingwall of NW fault that reactivated caldera margin[1]	≤ 1200 m, based on stratigraphic reconstruction	At least 400
Gold Hill	Tuff of Mt. Jefferson (26.4 ± 0.5[6]) near top of upper member, and overlying sedimentary rocks	26.4 ± 0.6 (K-Ar on vein adularia)[11]	Outside and 1.5 km west of inferred ring fracture zone of Mt. Jefferson caldera	Two small plugs inferred to mark buried ring fracture zone of Mt. Jefferson calders lie 1.8 km NE and 2.4 km SW; they are weakly bleached	Sheeted E-W to WNW-striking veins at right angles to strike of ring fracture of Mt. Jefferson caldera[1,2]	A few tens to hundreds of m; veins cut outcropping tuffaceous sedimentary rocks possibly correlatable with those that occured atop Round Mtn.	At least 150 (deepest level of old workings)
Corcoran Canyon	Tuff of Corcoran Canyon (27.2 ± 0.7[6]); source unknown; and tuff of Trail Canyon (23.6 ± 0.4[6])	Between 22.1 and 23.6 (K-Ar ages of fresh equivalent of altered tuff, and of overlying, unaltered tuff)[6]	Astride margin of Trail Canyon caldera	Altered, flow-layered plug 0.5 km E; other small intrusions 1 km N	Veins controlled by NE- and subordinate NW-striking, moderate to high-angle faults[1]	Ranges from 150 to ~ 270 m in different structural blocks of the deposit, based on stratigraphic reconstruction	At least 500
Barcelona (Flower and Van Ness Mines)	Paleozoic limestone, carbonaceous shale/mudstone, and metamorphosed equivalents[3,5]	Unknown	Outside and < 1 km south of topographic margin of Trail Canyon caldera	About 2.5 km WSW of small, porophyritic, flow-layered plug	High-angle, NW, NNE, and E-W faults; also, breccias and irregular veins controlled in part by bedding and folds[3,5]	Unknown	At least 150
Moores Creek	Lower member of the tuff of Mount Jefferson (26.4 ± 0.5[6])	Unknown	<1 km inside ring fracture of Mt. Jefferson caldera where reactivated by NW fault	2-3 km from weakly bleached, porphyritic plug marking ring fracture of Mt. Jefferson caldera	Steeply dipping, NW and N-S faults[1,3]	If age of mineralization same as other deposits near Mt. Jefferson caldera margin, then 700-800 m	At least 30

Table 4.

Alteration and mineralization in deposits associated with the Toquima caldera complex.

District	Primary ore and Sulfide Minerals	Oxidation	Hydrothermal Wallrock Alteration	Alteration Important vein types
Round Mountain	Electrum, pyrite, galena sphalerite, chalcopyrite pyrrhotite, tetrahedrite-freibergite, arsenopyrite, marcasite, realgar, proustite-pyrargyrite[1,7]	Deep; 200-400 m below present surface[2,7]	Early Ksp(I)-alb (Propylitic): adularia, albite, chlorite, calcite, pyrite, epidote Later Ksp(II) (potassic): adularia, white mica, pyrite, calcite Latest, high level silicification: quartz, adularia, pyrite, calcite?[7]	Early quartz—adularia-pyrite 'phenocryst overgrowth' veins and chlorite-pyrite-calcite veins Later microbreccia quartz-adularia-pyrite veins Latest cockscomb quartz-adularia veins[7]
Jefferson Canyon	Proustite-pyrargyrite, argentite-acanthite, hessite, pyrite, galena, electrum, freibergite-tetrahedrite, sphalerite, covellite, stibnite, realgar, chalcopyrite, bornite[1,3]	Shallow; 0-50 m (average 30 m) below present surface[1]	Broad volumes of early Ksp(I)-alb (propylitic; as at Round Mtn.) Later, structurally controlled Ksp(II) (potassic; as at Round Mtn.) and silicification[1]	Early chlorite-pyrite-calcite; Later quartz-carbonate; Latest pink carbonate[1]
Gold Hill	Electrum, pyrite[1]	Shallow; 0-30 m below present surface[1]	Downward-narrowing halos of silicification and bleaching on major veins[1]	Early anastomosing micro-breccia veins and clastic dikes Later E-W-striking, banded qtz-chalcedony veins Last adularia veins[1]
Corcoran Canyon	Proustite-pyrargyrite, argentite-acanthite, tetrahedrite-freibergite, polybasite, pyrite, chalcopyrite, sphalerite, galena, realgar[1]	Unknown	Broad volume of propylitic; superimposed by structurally controlled quartz-adularia and bleaching[1]	Multiple episodic generations: normally early pyrite, later quartz and quartz carbonate veins[1]
Barcelona (Flower and Van Ness Mines)	Cinnabar, stibnite, selenium (numerous base and precious metal sulfides in other mines of the district)[2,5,8]	Unknown	Structurally controlled silicification[3,8]	Quartz and quartz-carbonate veins[3,8]
Moores Creek	Pyrite[1,3]	Shallow; 0-15 m (average 10 m) below present surface[1]	Weak bleaching[1,3]	Cockscomb quarts-chalcedony veins[1,2]

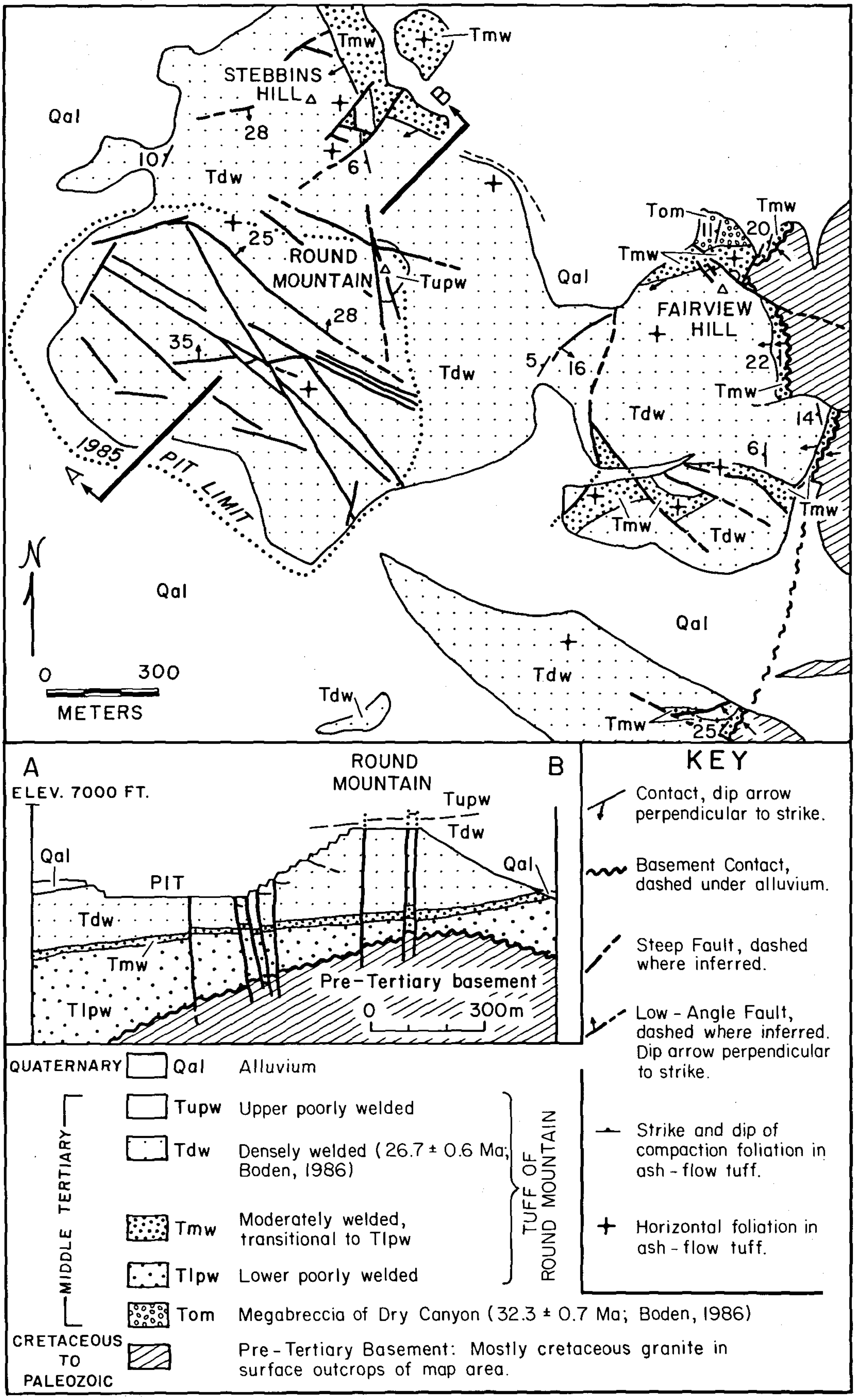


FIG.4. Geologic map and section of the Round Mountain Mine (after Sander, 1987).

overlying the tuff of Round Mountain. No intrusions that could have served as a heat source for the mineralizing hydrothermal system crop out at the mine, and none has been encountered in drilling to depths of about 1 km (Fig. 4).

The paleodepth to uppermost outcrops of mineralized tuff on Round Mountain is poorly constrained. Work by Boden (1986) suggests that no major tuff units overlay the mine at the time of mineralization, so that only the unknown thickness of the capping volcaniclastic sedimentary rocks, which could have ranged from a few tens to a few hundreds of meters, contributed to paleodepth. Sinter enclosed within the sedimentary section is reported by Tingley and Berger (1985). Later reports (Silberman and Berger, 1986; and Berger and Silberman, 1986) suggest that the banded chalcedony was not preserved as conformable beds on the section; but rather as blocks in coarse detrital rocks. In detail, the sinter did not overlie significant mineralization, and the enclosing sediments were cut by gold-bearing quartz-adularia veins. Thus the genetic link between sinter and mineralization is uncertain.

Known gold mineralization extends over a depth range of 750 m, from the top of Round Mountain before mining to the deepest mineralized intercepts in prevolcanic basement. That range is likely to increase as the basement becomes better tested by drilling.

Historic and recent mining have exploited gold contained in the outcropping densely welded portion of the tuff (Fig. 5). Important targets of the early, selective miners included low-angle veins that were reopened by a variety of vein types and northwest-striking, moderately to steeply dipping quartz-adularia veins of several characteristic styles. Among those styles are coarse, cockscomb quartz-adularia-electrum veins, medium-grained sugary quartz-adularia-electrum veins, and microbreccia quartz-adularia-pyrite-electrum veins (Ferguson, 1921; Tingley and Berger, 1985; Sander, 1987; Fig. 5). In the modern open pit, the type of vein most closely associated with high gold grades in blast holes consists of northwest-striking joints distinguished by quartz overgrowths on intersected quartz phenocrysts and by adularia overgrowths on intersected altered sanidine and plagioclase phenocrysts (Sander, 1987). Such "phenocryst-overgrowth" veins host isolated pyrite cubes that commonly bear blebs of visible gold. Gold locally is present in clay- and Fe/Mn-oxide-coated fractures of many orientations. These occurrences may represent remobilization of gold out of original quartz-adularia veins during later stages of the 25 to 26 Ma event, during a possible low-grade hydrothermal event coincident with the onset of basin-range block faulting at 9 to 12 Ma, and/or during weathering (Ferguson, 1921; Tingley and Berger, 1985; Sander, 1987). The 9 to 12 Ma age is suggested by contemporaneity of the documented onset of block faulting in other parts of Nevada with K-Ar ages of fine-grained alunite coating fractures at the mine (Tingley and Berger, 1985; Sander, 1987).

The bulk of reserves lies within lower poorly welded tuff, where important stratal control of permeability augmented northwest-trending structural permeability (Sander, 1987; Fig. 5). Sparse overgrowth-type veins and the highest gold grades do occur in lower poorly welded tuff along projections of outcropping, sheeted vein sets hosted by overlying densely welded tuff. However, ore grade mineralization also occurs as much as a few hundred meters laterally away from those inferred conduits. In the lateral mineralized zones, veins do not occur; grade variations are coincident with lithic trains in the tuff that mark individual flow units. The flows with larger or more abundant pumice (i.e., greater primary permeability) are better mineralized than those with smaller or less abundant pumice. Early vapor-phase alteration preserved primary permeability in the already more permeable zones by altering volcanic glass to more stable quartz and K-feldspar, delicately preserving open space. On the other hand, glass in flows with less primary permeability escaped early vapor-phase alteration. It was altered readily to clay during hydrothermal alteration, sealing primary open space.

Primary sulfide minerals at Round Mountain are dominated by pyrite. Other sulfides occur in trace amount and are listed in Table 4. The primary sulfides have been oxidized to a relatively uniform elevation, which lies 200 to 400 m below the present surface. Sander (1987) concludes that oxidation probably was due to weathering above a deep water table.

Alteration of the tuff of Round Mountain includes early, propylitic alteration that is overprinted by later "bleaching" encompassing several different mineral associations formed at different times and under different hydrothermal conditions. The latest important alteration is silicification, present at high levels in the system.

Detailed petrography indicates that hydrothermal feldspar minerals, especially K-feldspar, are formed or preserved, rather than destroyed, in most alteration types at the mine. On the other hand, phyllosilicate minerals re-equilibrate extensively during successive, overprinted alteration events, wiping out evidence of earlier events. Thus, while phyllosilicate minerals determine important mappable rock properties such as color, they are not as useful as the more cryptically altered feldspar minerals for tracing multiple alteration events (Sander, 1987).

Two major feldspar-keyed alteration associations occur at Round Mountain—K-feldspar(I)-albite (Ksp(I)-alb) and K-feldspar(II) (Ksp(II)). Ksp(I)-alb is the earliest hydrothermal alteration and represents nearly isochemical, propylitic alteration. Sanidine phenocrysts are replaced by pure K-feldspar, plagioclase by albite, and biotite by chlorite. Pyrite, calcite, smectite, epidote, and illite also occur. The intensity of Ksp(I)-alb alteration can be estimated in thin section by estimating the percent replacement of magmatic sanidine phenocrysts by Ksp(I). Tuff in which sanidine phenocrysts are 100 percent altered to Ksp(I) forms broad, pervasive, halos on the same northwest faults that guided slightly later fluids that formed the gold-bearing, phenocryst-overgrowth veins. The halos are wider in more permable poorly welded tuff than in less permable densely welded tuff (Sander, 1987; Fig. 5).

Later Ksp(II) alteration results in bleaching of affected rock and represents strong potassium metasomatism. Albite pseudomorphs after plagioclase are replaced by K-feldspar, as are the matrix and pumice spherulites. Biotite sites, probably previously chloritized, are replaced by coarse white mica. Sanidine retains its magmatic composition where Ksp(II) alteration overprints rock not previously completely altered to Ksp(I)-alb. Intensity of Ksp(II) alteration can be estimated in thin section by percent replacement of plagioclase phenocrysts by Ksp(II). Fringing Ksp(II) alteration is bleached tuff in which the Ksp(I)-alb feldspar association is preserved, but chlorite is altered to white mica or mixed-layer illite-smectite. At Round Mountain Ksp(I)-alb and Ksp (II) alteration were guided by different northwest fractures (Sander, 1987; Fig. 5). Ksp(II) alteration overprints lower poorly welded tuff earlier altered to 100 percent Ksp(I)-alb. However, in overlying densely welded tuff Ksp(II) alteration affects rocks earlier only weakly altered to Ksp(I)-alb.

At high levels in the system, all albite (plagioclase) in the rock, remnant from Ksp(II) alteration, and all phyllosilicate minerals are replaced by quartz ($\pm$ calcite?). Magmatic sanidine, Ksp(I), and Ksp(II) are perfectly preserved. This late silicification is controlled by essentially the same fractures that guided Ksp(II) alteration (Fig. 5). There is a 10 to 100 m-scale halo around silicified rock in which the remnant albite, chlorite (and, locally, white mica) are altered to mixed-layer smectite-illite creating a style of bleaching mineralogically distinct from that fringing Ksp(II) alteration (Sander, 1987).

The widespread alteration types discussed above involve successive replacement of plagioclase by albite and K-feldspar and replacement of plagioclase and albite by clays. Alteration resulting in complete replacement of plagioclase or albite by white mica, and alteration resulting in complete replacement of K-feldspar by any mineral are rare. For example, centimeter- to meter-scale bleached halos occur on strongly illitized fault gouge are present locally in the pit. The inner few centimeters of those halos contain leached, silicified, or sericitized plagioclase and sanidine phenocrysts.

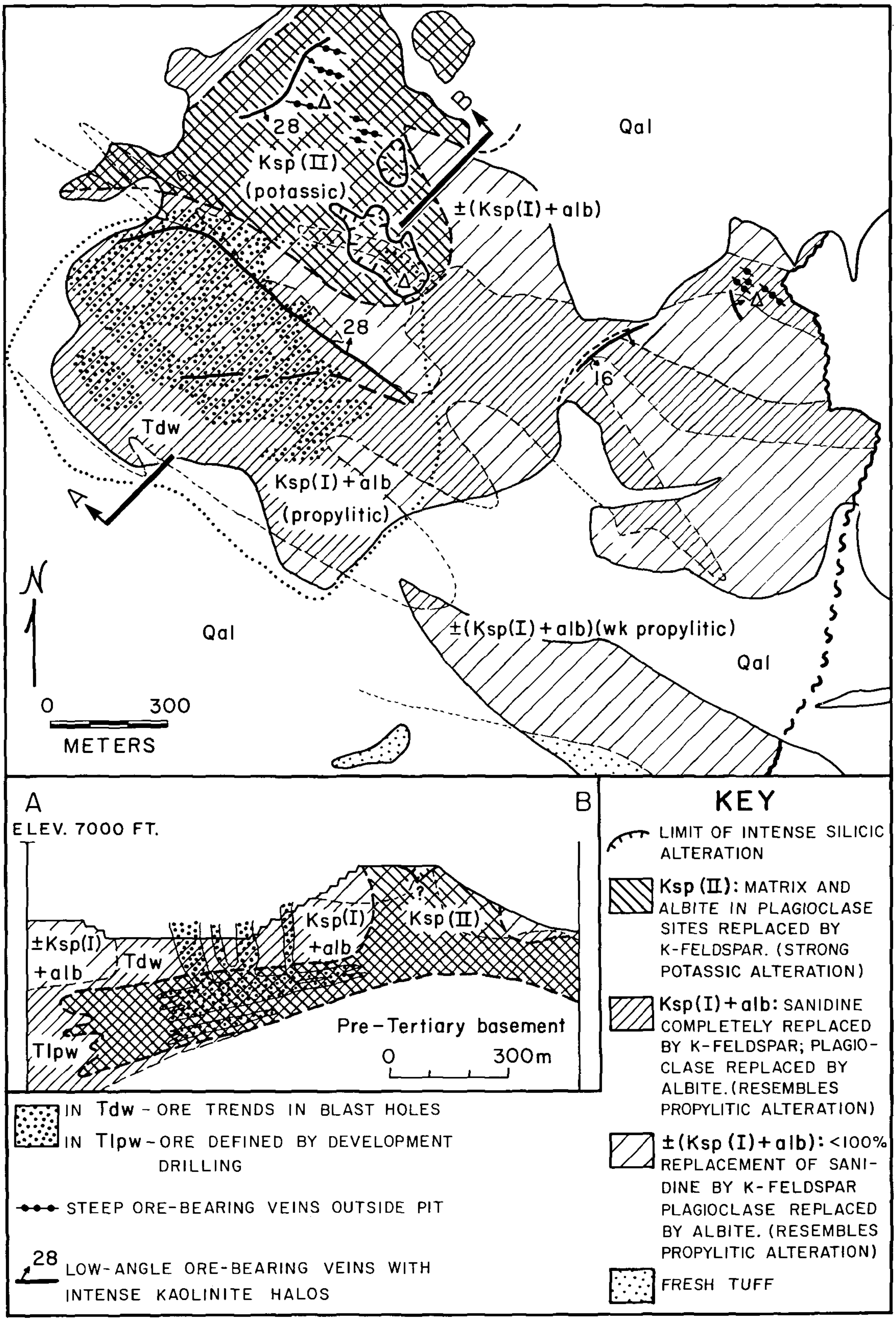


FIG. 5. Alteration and mineralization at the Round Mountain Mine (after Sander, 1987). K-feldspar is stable in all alteration types.

Most gold in densely welded tuff of Round Mountain occurs in that portion of 100 percent Ksp(I)-alb alteration cut by slightly later phenocryst-overgrowth veins; the outcropping, later Ksp(II) alteration zone (guided by markedly different northwest fractures than guided earlier Ksp(I)-alb alteration) contains isolated, high-grade gold veins but no bulk-minable tonnage. In poorly welded tuff at depth, stratabound conduits of fluid flow did not change with time as did structural conduits in densely welded tuff. Therefore, pervasive Ksp(I)-alb alteration, gold mineralization, and Ksp(II) alteration are all coincident (Sander, 1987).

Assay data from the mine and from Tingley and Berger (1985) can be interpreted to suggest that, where Ksp(II) alteration is spatially separate from Ksp(I)-alb alteration in weathered, outcropping densely welded tuff, veins hosted by Ksp(II) alteration have lower gold and higher silver values than veins hosted by Ksp(I)-alb alteration. Furthermore, thallium, antimony, arsenic, tungsten, and molybdenum anomolies are associated with Ksp(II) rather than Ksp(I)-alb alteration.

The present mining operation exploits bulk-mineable sets of sheeted veins hosted by Ksp(I)-alb alteration, with or without alteration halos that alter Ksp(I)-alb-related chlorite to mixed layer clays or white mica. Whereas the mine produces gold and silver in a 2:1 ratio, the ratio of gold to silver in the open pit *in situ* ranges from 1:5 to 1:10. The *in situ* ratios decreases markedly in the outcropping Ksp(II) alteration zone outside the present orebody. It also may decrease with depth where sulfides are unweathered and where Ksp(I)-alb and Ksp(II) alteration are superimposed in lower poorly welded tuff.

The Jefferson Canyon deposit

The Jefferson Canyon district historically produced about 1,000 oz of gold and 300,000 oz of silver (Table 2). Recent exploration has defined new resources that occur in two separate zones that collectively contain about 73,000 oz of gold and 15.5 million oz of silver (Table 2; Fig. 6). Host for most of the mineralization is the outcropping densely welded upper member of the tuff of Mount Jefferson. The subcropping, lower, less welded member in Jefferson Canyon has not as yet been found to host significant mineralization analogous to that hosted by lower poorly welded tuff at the Round Mountain Mine. Paleozoic basement rocks host only a small amount of mineralization.

Whereas the Round Mountain Mine lies about 6 km outside and southwest of the margin of the Mount Jefferson caldera, the Jefferson Canyon deposit occurs directly on the margin of the caldera. In Jefferson Canyon, the tuff of Mount Jefferson is juxtaposed against Paleozoic and Cretaceous rocks, similar to those at Round Mountain, by the northwest-striking Jefferson Canyon fault (Figs. 2, 3, and 6). That fault is one of those regional, northwest-striking faults that may have guided caldera collapse and that underwent periodic, postvolcanic reactivation (Boden, 1986).

The tuff of Mount Jefferson is intruded in the historic mine area by rhyolite and rhyolite breccia in a variety of dikes, sills, and domes. The intrusive rock is a flow-layered, altered quartz-eye rhyolite that, in places, bears close spatial and probable temporal relations with mineralization.

No direct age of mineralization is currently available for alteration associated with the mineralization at Jefferson Canyon. Shawe and others (1986) published a 25.9 ± 1.1 Ma age on zircon from a mineralized rhyolite plug in the deposit. Because Nash (1972) in a reconnaissance study reported fluid inclusion homogenization temperatures in the deposit of 250° C and because Naeser and others (1980) reported annealing of zircon fission tracks at temperatures of between 175 and 225° C, the fission track age may reflect the age of mineralization. That age is also analytically indistinguishable from the age of the host tuff of Mount Jefferson (Table 1).

Reconstruction of the volcanic stratigraphy at the probable time of mineralization

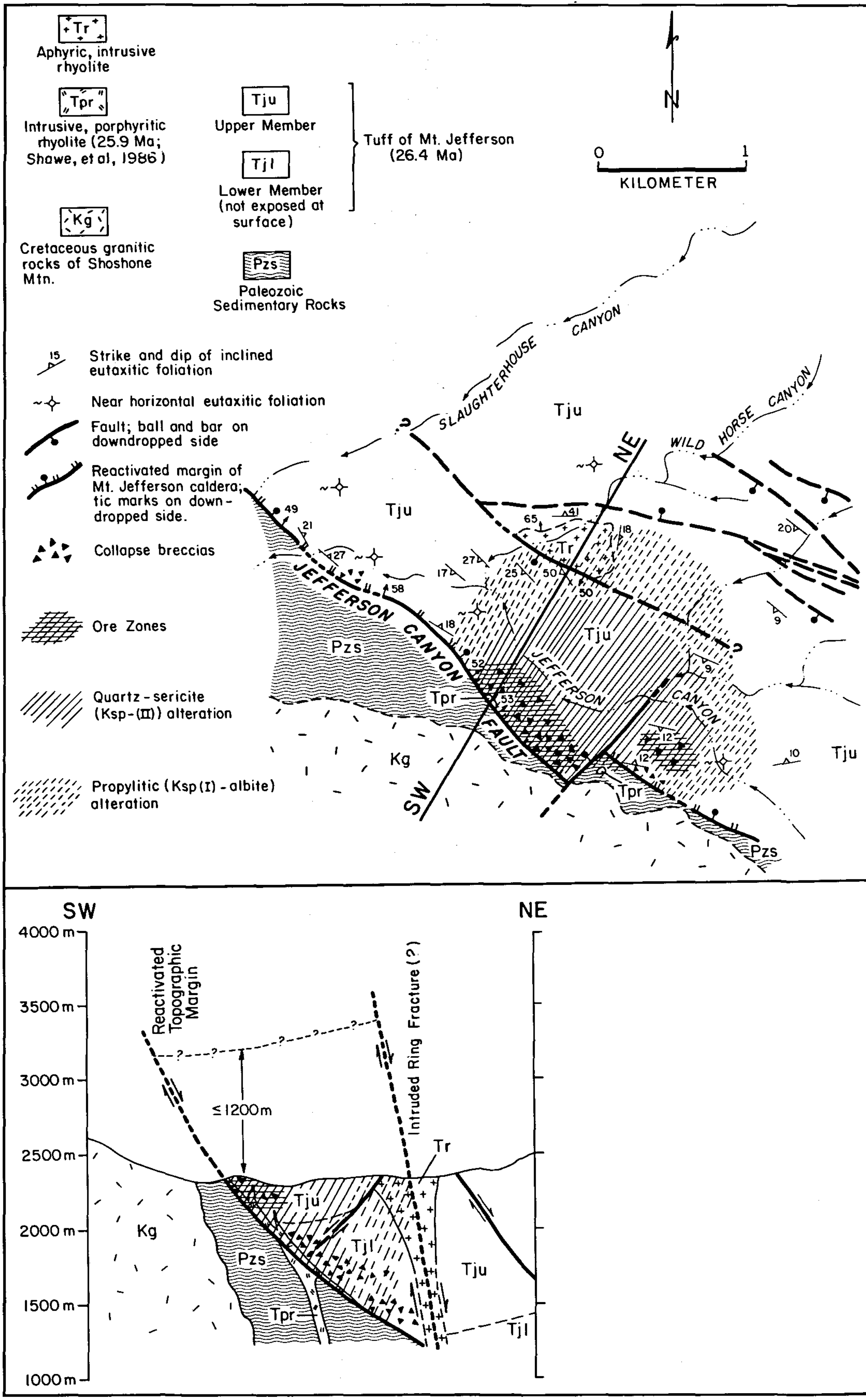


FIG. 6. Geology, alteration, and mineralization at the Jefferson Canyon deposit in plan and section.

suggests a paleodepth to presently exposed mineralized outcrops of at least a few hundred to a maximum of 1,200 m (Fig. 6). Known mineralization extends from the current surface to a depth of at least 400 m.

Structural controls of mineralization in Jefferson Canyon are the northwest-striking, moderately north-dipping Jefferson Canyon fault and its associated, subparallel, hanging wall fractures (Fig. 6). Gold, silver, and copper mineralization occurs mostly in quartz ± carbonate veins. Hydrothermal, ore-related minerals at Jefferson Canyon include abundant pyrite, common hessite, ruby silver minerals, electrum, chalcopyrite, galena, sphalerite, and trace amounts of other minerals listed in Table 4. Unlike at Round Mountain, oxidation of primary sulfides at Jefferson Canyon is quite limited, commonly extending no deeper than 50 m, and locally less than 10 m.

Recent reconnaissance studies have shown that the same feldspar-keyed alteration types recognized at Round Mountain (Sander, 1987) exist in Jefferson Canyon. A wide Ksp(I)-alb (propylitic) halo extends over a 4 km^2 area and is related in intensity to the Jefferson Canyon fault and its hanging wall structures. Overprinting this early alteration is a one km^2 area of strong Ksp(II) (potassic; quartz-adularia-sericite) alteration. In Jefferson Canyon, the Ksp(II) alteration zone hosts silver-gold-copper-bearing, vuggy quartz-carbonate veins that in aggregate form the currently identified mineral resource. Assays from outcrop and drill holes indicate that the gold:silver ratio ranges from 1:10 to 150. The ratio is greater in Ksp(I)-alb than in Ksp(II) alteration, as at Round Mountain. However, only a small zone of high absolute gold grades analogous to the orebody at Round Mountain has been found to date in Jefferson Canyon.

The Gold Hill Mine

Historically, about 19,000 oz of gold and 185,000 oz of silver were produced from the Gold Hill Mine (Table 2). The mine is located within the tuff of Mount Jefferson, immediately adjacent to and outside of the structural margin of the Mount Jefferson caldera (Figs. 2 and 3). Several small rhyolitic plugs inferred to mark the structural margin of the caldera, crop out within about one km of the mine, but no intrusions crop out in the mine area itself.

A sequence of poorly welded pumice ignimbrites and interbedded tuffaceous sandstones and siltstones is in fault contact with the tuff of Mount Jefferson in the vicinity of the headframe. The sequence is inferred to overlie the tuff based on lithologic similarity with tuffaceous sedimentary rocks that originally capped the tuff at Round Mountain 6 km to the south. As at Round Mountain, the sedimentary section at Gold Hill is cut by gold-related quartz veins. Gold and silver mineralization is found in east-west-striking, 0.2 to 1.0 m wide, banded, chalcedonic to crustiform quartz veins, the largest of which is the Gold Hill vein. The quartz veins have been offset by later adularia ± quartz veins, adularia from which has been dated at 26.4 ± 0.5 Ma (Boden, this study).

The minimum paleodepth of gold deposition at Gold Hill has the same constraints as at Round Mountain—probably a few tens to a few hundred meters. Mineralization extends for at least a depth range of 150 m, from the surface to the bottom of the deepest historic workings.

Opaque minerals are dominated by pyrite, with minor electrum and possible rare silver sulfosalts. Oxidation of primary sulfides extends only to a depth of 30 m or less, based on exposures in the old workings.

The tuff of Mount Jefferson is silicified and bleached as far as 100 m on either side of the main Gold Hill vein and subparallel structures. Silicification and bleaching diminish to the east along the veins and with depth in the old workings. No attempt has been made to evaluate feldspar-based alteration styles at Gold Hill, although the characteristics and distribution of the megascopic alteration resemble those in the silicified and Ksp(II)-altered upper portions of Round Mountain.

The Corcoran Canyon prospect

Drilling in Corcoran Canyon on the east side of the Toquima Range (Figs. 2 and 3) has recently encountered high grade, silver-gold veins. Hosts for mineralization include the 27.7 ± 0.7-Ma-old tuff of Corcoran Canyon and the 23.6 ± 0.4-Ma-old tuff of Trail Canyon (Fig. 7). The tuff of Corcoran Canyon was derived from an unknown source outside the Toquima caldera complex and is in fault contact with the tuff of Trail Canyon along a northeast-striking fault that in part marks the margin of the Trail Canyon caldera. Both the tuffs of Trail Canyon and Corcoran Canyon are intruded by a variety of altered, rhyolitic to dacitic plugs and domes.

Although no direct date of alteration is currently available at Corcoran Canyon, the age of hydrothermal activity is well constrained—unaltered tuffs of Road Canyon (23.6-22.1 Ma) unconformably overlie altered 23.6-Ma-old tuff of Trail Canyon. Thus, mineralization closely followed collapse of the Trail Canyon caldera.

Reconstruction of the volcanic stratigraphy suggests that the minimum paleodepth to present mineralized outcrops ranged from a minimum of about 150 m to a maximum of about 270 m (Fig. 7). Results from drilling indicate that mineralization extends from the present surface to depths of at least 500 m.

Primary controls of mineralization in Corcoran Canyon are large, moderately to steeply dipping, northeast-striking, oblique-slip faults and, to a lesser extent, steeply dipping, northwest-striking, normal faults. Mineralization and alteration occur along the structural margin of the Trail Canyon caldera, extending for several kilometers outside the margin into the tuff of Corcoran Canyon along a major, northeast-striking shear zone (Fig. 7). Several altered, rhyolitic, porphyritic plugs exist in the eastern portion of the alteration zone.

Gold and silver occur in a variety of vein types developed in sheeted and stockwork zones related to major faults and fault intersections. Multiple generations of veins are recognized, evolving in mineralogy with time from pyrite-quartz-carbonate to quartz to carbonate. Primary sulfide minerals include pyrite and a wide variety of silver sulfosalts and silver and base metal sulfides (Table 4). The sulfides have been oxidized to depths of as much as 30 m, although fresh sulfides locally occur in outcrop.

No detailed studies have been made of alteration at Corcoran Canyon. Generalized field descriptions of alteration define a broad area of about 10 km^2 that has been propylitized (chloritized) along the southeast margin of the Trail Canyon caldera. The alteration extends eastward for about 3 km into the tuff of Corcoran Canyon along the northeast-striking fault zone (Fig. 7). Within the broad "propylitic" zone, smaller areas of bleaching, quartz-adularia alteration, and silicification are localized by major faults and fault intersections. As at Round Mountain and Jefferson Canyon, feldspar minerals are preserved in original magmatic feldspar phenocrysts through nearly all alteration; there is no extensive alteration of K-feldspar to phyllosilicate minerals. If the analogy with alteration at Round Mountain is extended, the wide propylitic zone may be expected to contain Ksp(I)-alb alteration and the bleaching and quartz-adularia alteration to contain, at least in part, Ksp(II) alteration.

Other deposits

Other mineralized areas which may be related to the Toquima caldera complex include the Moores Creek prospect and the Barcelona (Flower and Van Ness Mines) area (Figs. 2 and 3). The Flower and Van Ness Mines appear to lie along the southwestward extension of the northeast-striking fault guiding mineralization in Corcoran Canyon (Fig. 3).

At Moores Creek, a wide area of weak bleaching alteration has affected the lower member of the tuff of Mount Jefferson (26.4 q 0.5 Ma). Within this alteration zone exist sparse, 0.5 to 1.0 m wide, north-south striking, crustiform, gold-silver-bearing quartz veins. These veins are all found within 1 km of and inside of the northwest margin of the Mount Jefferson caldera. No direct age of alteration is available.

The Barcelona district is noted mostly for its copper-molybdenum-lead-gold-silver mineralization associated with skarns developed around Cretaceous intrusions (Ervine, 1972; Kleinhampl and Ziony, 1984). The stibnite- and cinnabar-bearing veins exploited at the Flower and Van Ness Mines, however, probably do not belong to the skarn environment. The east-west and northeast trends of the mineralization, parallel to the nearby margin of the Trail Canyon caldera, suggest that the cinnabar and stibnite veins could be epithermal and Tertiary in age, related to the Toquima caldera complex. As such they may have been superimposed on the much older Cretaceous skarns, which formed at much deeper levels.

Discussion

Calderas and Eruptive Products

Eruption of the tuffs of Moores Creek, Mount Jefferson, and Trail Canyon led to collapse of three calderas that comprise the Toquima caldera complex. The age and size of the calderas decrease from northwest to southeast—a trend that parallels regional northwest-striking faults. Moreover, margins of the calderas are in part controlled by those regional faults,

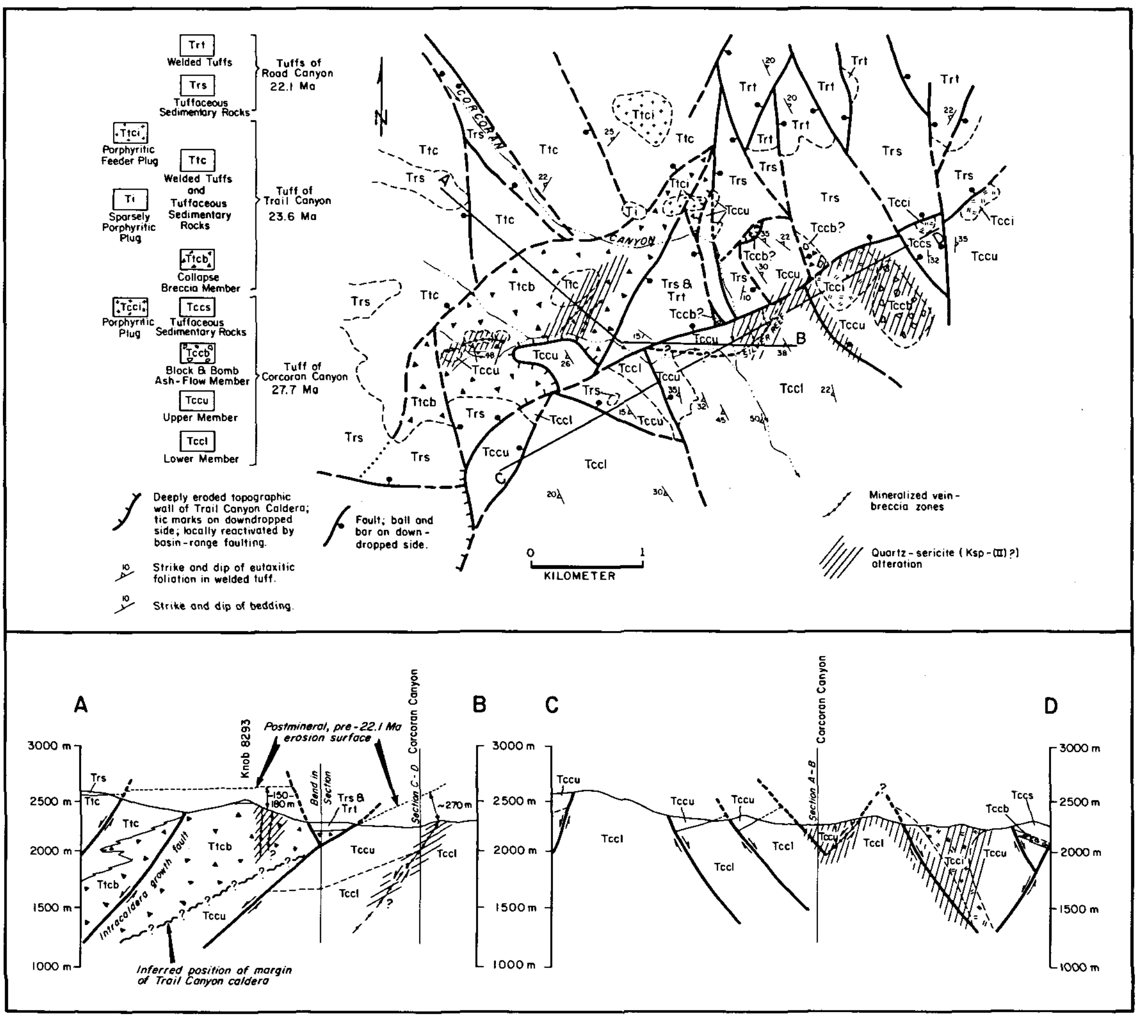


FIG. 7. Geology, alteration, and mineralization at the Corcoran Canyon prospect in plan and section.

suggesting fundamental structural control in the rise and eruption of magma and collapse of volcanic centers.

Due to subsequent faulting and erosion, outflow equivalents of the intracaldera tuffs of Moores Creek and Trail Canyon are not now exposed. Boden (1986) concluded, however, that the tuff of Round Mountain, based on mineralogical, geochemical, and K-Ar age data, is an early outflow product of the Mount Jefferson caldera and correlatable to the lower intracaldera member. In contrast, Berger and others (1986) interpreted the tuff of Round Mountain to be unrelated to the tuff of Mount Jefferson and to have a separate source area— the "Round Mountain caldera." Furthermore, they interpret the Round Mountain mine to lie in the ring fracture zone of the "Round Mountain caldera." Berger and others (1986) cited the following evidence in support of a separate source area for the tuff of Round Mountain: (a) welded ash-flow tuff megabreccia underlies the tuff of Round Mountain in the vicinity of the mine; (b) the 450 m thickness of the tuff of Round Mountain is unusually thick for an extracaldera ash-flow tuff; (c) the rocks at the Gold Hill Mine north of Round Mountain are similar to those at Round Mountain and are overlapped by the tuff of Mount Jefferson; and (d) the tuffs of Round Mountain and Mount Jefferson have different modal mineralogies and chemical compositions.

Although the tuff of Round Mountain does overlie megabreccia, called the megabreccia of Dry Canyon (Boden, 1986), the megabreccia is clearly older than and unrelated to the tuff of Round Mountain based on (a) the presence of an angular unconformity between the two units of up to 15° (Sander, 1987); (b) modal and chemical differences between the megabreccia of Dry Canyon and overlying tuff of Round Mountain (the former is a sanidine-poor, biotite-rich rhyodacite (69.2 wt.% SiO_2; Shawe and Lepry, 1985), and the latter, is a biotite-poor, high-silica rhyolite (77.5% SiO_2) at its base, and (c) the 32.3 ± 0.7-Ma-old age of the megabreccia of Dry Canyon, about 6 Ma older than the tuff of Round Mountain (Boden, 1986). Therefore, although the megabreccia of Dry Canyon may mark the margin of a caldera now largely buried beneath Big Smoky Valley, there is no evidence that the overlying tuff of Round Mountain was derived from such a source area. Indeed, the basal part of the tuff of Round Mountain contains no welded ash-flow tuff megabreccia, but only local lithic-rich zones (clasts generally less than 1 m across) in poorly welded tuff.

The 450 m thickness of the tuff of Round Mountain is not unusually thick for an outflow ash-flow tuff because paleotopographic relief can result in ponding and thick accumulations. For example, the Fish Canyon Tuff is greater than 1.4 km thick where it inundated an older caldera 20 km from its source (Steven and Lipman, 1976). Indeed, such an outflow ponding relationship seems analogous to the tuff of Round Mountain, which also appears to have infilled an older caldera as evidenced by the underlying megabreccia of Dry Canyon.

We agree with Berger and others (1986) that poorly welded tuff and tuffaceous sedimentary rocks exposed at the Gold Hill mine, have similar lithologic and stratigraphic relations to those at Round Mountain. These stratigraphic relations are also consistent with those in the Mount Jefferson caldera, where tuffaceous sedimentary rocks occur locally near the top of the lower member and reinforce the interpretation that the intracaldera lower member and outflow Round Mountain member are stratigraphically correlatable.

Modal and chemical differences between the tuffs of Round Mountain and Mount Jefferson are not sufficient to preclude the two units from being cogenetic. As demonstrated by Boden (1986), modal and chemical trends of the Round Mountain member are partly overlapped and extended by the lower and upper members of the tuff of Mount Jefferson. Thus differences in mineralogy and chemical composition, as cited by Berger and others (1986), can be explained by comparing different stratigraphic levels in a single compositionally zoned eruptive unit. As a result, we maintain that the Round Mountain member and intracaldera lower member of the tuff of Mount Jefferson are indeed outflow and intracaldera equivalents erupted from the Mount Jefferson caldera.

Caldera resurgence, in the form of structural uplift and doming related to caldera formation, is only minor in the Toquima caldera complex based on (a) the lack of an angular unconformity between eruptive units of the caldera complex and younger volcanic rocks (i.e., the 22-23-Ma-old tuffs of Road Canyon); (b) the dearth of hydrothermal alteration along intracaldera faults; and (c) the restricted occurrence of small plugs or dikes along caldera margins and lack of central intrusions or stocks, despite deep levels of erosion (greater than 2.5 km). Although there is only limited caldera resurgence, the Toquima caldera complex is strongly mineralized and ages of mineralization coincide with ages of caldera volcanism. As discussed below, controls other than caldera resurgence appear to have fostered mineralization in the complex.

Volcanism and Mineralization

A review of Table 3 and Figure 3 reveals a close temporal and spatial relation between caldera volcanism and precious metals mineralization. Mineralization at Round Mountain, Gold Hill, and Jefferson Canyon closely followed, within the limits of resolution of radiometric dating, development of the Mount Jefferson caldera. Similarly, mineralization at Corcoran Canyon shortly followed collapse of the Trail Canyon caldera.

This close temporal association between caldera volcanism and mineralization in the Toquima caldera complex stands in apparent opposition to other caldera-hosted deposits where studies have shown that significant precious metals mineralization formed several million years after caldera-related, calk-alkaline, igneous activity. Such deposits include Goldfield, Nevada (Ashley, 1979), and the major gold-silver deposits of the San Juan volcanic field in southwestern Colorado, including Summitville, Camp Bird, Idarado (Lipman and others, 1976); Creede (Bethke and others, 1977); and Sunnyside (Casadevall and Ohmoto, 1977). In those systems, ore was deposited in caldera-related structures but was formed by much younger igneous-hydrothermal events unrelated to caldera-associated magmatism.

The Toquima caldera complex underwent only limited caldera resurgence. As a result, the interior portions of all the calderas are notable for their dearth of alteration, even where cut by numerous faults. The important precious metals deposits of the complex are developed primarily along the margins of the Mount Jefferson and Trail Canyon calderas, where the margins are coincident with the faults of the northwest-striking and northeast-striking sets. Where the margins have not been reactivated by those faults, alteration and mineralization are only weakly developed. The most important of the deposits of the complex, the Round Mountain Mine, is not directly spatially associated with any of the three Toquima complex calderas: the primary control consists solely of the northwest faults. A secondary control of unknown significance is the possible buried caldera margin represented by the 32-Ma-old megabreccia of Dry Canyon.

Evidence presented in this paper and in Boden (1986) suggests that the northwest- and northeast-striking, moderately to steeply dipping faults formed before formation of the Toquima caldera complex and may have influenced the positions and shapes of the eruptive centers. The combination of faulting and caldera collapse established deeply penetrating zones of high permeability that promoted circulation of hydrothermal fluids. As volcanism waned in a given center, continued minor displacement on the faults fractured overlying ash-flow tuffs, extending the zones of structural permeability to high levels and permitting fluid access to the epithermal environment. Thus, the close timing of extensional and oblique-slip faulting and volcanism at the Toquima caldera complex was perhaps a necessary condition for producing precious metals mineralization temporally related to the caldera cycle. Caldera resurgence, however, was not important in controlling the development of the epithermal mineralization (cf. Smith and Bailey, 1968).

Historically, the great bulk of gold production from volcanic rocks in Nevada is from andesitic host rocks (Silberman and others, 1976). Silicic ash-flow tuffs, although the most voluminous igneous rock type exposed in Nevada, host only five of the 98 precious metals districts that have supported production of $1 million or more (McKee, 1979). However, based on findings from this study, silicic ash-flow tuffs and related silicic lavas and intrusions of mid- Tertiary age in central Nevada do represent promising host rocks for precious metals deposits, especially where they have been cut by faults related to pre-basin-range style extension. The favorability of the silicic rocks is borne out not only by recent discoveries at Jefferson Canyon and Corcoran Canyon in the Toquima complex, but also by recent discoveries outside the complex at Rawhide, Nevada (J. Black, 1986, pers. comm.) and Paradise Peak, Nevada (Thomason, 1986).

Deposit-scale environments

Paleodepths to present mineralized outcrops in deposits of the complex, where known, range from a few tens to perhaps 1,200 m (Figs. 4, 6, 7, and Table 3). The shallowest of the deposits could have been the Round Mountain and Gold Hill Mines, where volcaniclastic sedimentary rocks capping the host ash-flow tuffs may not have been overlain by major, younger ash-flows at the time of mineralization. Reports of sinter in the volcaniclastic sedimentary rocks at Round Mountain do not constitute evidence of the exact paleosurface because uncertainties exist about whether the sinter was preserved as conformable beds or as clasts in the sedimentary rocks and because the enclosing sedimentary rocks are cut by gold-bearing veins. Hydrothermal fluids that formed gold-bearing veins may have formed sinter at the paleosurface, but there is no compelling evidence that they did. On the other hand, the Jefferson Canyon and Corcoran Canyon deposits represent somewhat deeper levels of exposure, as great as 1,200 m at Jefferson Canyon (Figs. 6 and 7).

Probable paleodepths and vertical extents of mineralization at all the deposits of the complex are well within the range of explored depths of active hot springs systems summarized by Ellis (1979). For example, Wairakei and Broadlands, New Zealand, have been drilled to 2.3 and 2.4 km, respectively, and The Geysers, California, to 2.8 km. Thus, all of the hydrothermal systems represented by the deposits of the complex may have had surface expression.

The range in paleodepths is reflected in the variations in contained metals among the deposits. Round Mountain contains only a trace of sulfides other than pyrite and minimal base metal values. The gold to silver ratio averages about 1:5 to 1:10 within the bulk mineable part of the deposit extending to somewhat lower values in other parts of the system. Similarly low base metal values and high gold:silver ratios can be inferred at Gold Hill from the historical production data and sulfide mineralogy (Tables 2, 4).

The deeper Jefferson Canyon and Corcoran Canyon deposits contain much lower gold:silver ratios, ranging from 1:10 to 1:1000 in the explored parts of the systems. The content of base metals is correspondingly much greater.

One complication in relating metal content to simple paleodepths at the deposits is that inferred paleodepths are paralleled by the association of individual deposits with possible coeval intrusions. No such intrusions crop out at the Gold Hill or Round Mountain Mines or has been encountered in drilling as deep as 1 km under the Round Mountain Mine. However, mineralized and altered rhyolite plugs and dikes do crop out at Jefferson Canyon and Corcoran Canyon. Those rocks must have been intruded in the short time span between eruption of the tuffs and alteration, so could be distinctly ore-related. Thus, apparent depth zoning instead may reflect variations in proximity to ore-related intrusions.

Another distinction among the deposits is the composition of host rocks penetrated by possible ore-related intrusions. At the relatively silver-rich Jefferson Canyon and Corcoran

Canyon deposits, the intrusions reached well up into the volcanic section. On the other hand, any possible intrusion inferred under Round Mountain could have penetrated only as far as the carbonaceous, pyritic Paleozoic rocks.

Differences in depths of oxidation at the deposits may be related to differential rates of uplift and erosion associated with basin-range faulting. For example, the partially oxidized Jefferson Canyon deposit is exposed in relatively steep terrain with deeply incised, V-shaped valleys—an environment in which active uplift and erosion have outpaced rates of oxidation. In contrast, the deeply oxidized Round Mountain deposit appears to have existed at minimal depths throughout its post-mineral history. For much of that history, not only was the rate of erosion low, but alluvium from nearby highlands was actually being deposited around it.

Alteration and mineralization

All the deposits in the complex are typified by a general paucity of large-scale hydrothermal brecciation. Some of the higher grade veins mined historically at Round Mountain and Jefferson Canyon did contain breccias, and barren clastic dikes can be mapped at Round Mountain. In addition, breccia of uncertain origin locally crops out in the Corcoran Canyon prospect. However, the vast majority of mineralization in each system, especially bulk-minable mineralization, was emplaced by fluids permeating along faults and related joints and through rocks that had high primary permeability.

Alteration at all the deposits consists of early propylitic alteration (Ksp(I)-alb at Round Mountain and Jefferson Canyon), overprinted by several different styles of bleaching, and latest silicification. At Round Mountain, the best studied of the deposits, different styles of bleaching include 1) alteration of Ksp(I)-alb related chlorite to mixed-layer clay or white mica, preserving Ksp(I)-alb feldspars (in part the fringe of Ksp(II) alteration); 2) alteration of chlorite to white mica and of albite to K-feldspar (Ksp(II) alteration); 3) alteration of albite and white mica to mixed-layer clay (fringe of late, high-level silicification). Alteration destroying K-feldspar is both rare and late.

At Round Mountain, bulk-mineable gold mineralization occurs where Ksp(I)-alb alteration is cut by quartz-adularia veins with no halos or bleached chlorite halos, and where Ksp(I)-alb and Ksp(II) alteration overlap. Ksp(II) alteration does not contain bulk-mineable gold mineralization where it affects tuff previously unaltered to Ksp(I)-alb. Ksp(II) alteration contains higher silver:gold ratios, as well as higher absolute silver and lower absolute gold values, than Ksp(I)-alb alteration. At Jefferson Canyon, bulk-minable silver mineralization is contained in Ksp(II) alteration.

No advanced argillic style alteration (strictly defined by alteration of muscovite to pyrophyllite or kaolinite; Hemley and Jones, 1964) is present at any of the deposits. Alunite, commonly used as a suggestion of advanced argillic alteration in epithermal systems, occurs only in or near fractures in rocks in which hydrothermal sulfides have been oxidized, probably due to weathering. Alunite is distinctly not associated with the typical enargite-bearing sulfide mineralogy related to high sulfidation states at other deposits with well-documented advanced argillic alteration such as Goldfield, Nevada (Ashley, 1974), Pyramid, Nevada (Wallace, 1979), and Summitville, Colorado (Hayba and others, 1985). At Round Mountain alunite most likely postdates gold mineralization by many million years.

Wallace (1979) divided precious metals deposits in Nevada into those that may lie above porphyry copper deposits and those that probably do not, chiefly on the basis of associated advanced argillic alteration. The deposits of the Toquima caldera complex, lacking such alteration, clearly fall into the group without likely porphyry affinities. The character of their roots is unknown at this time, but is being tested by new drilling at Round Mountain and Corcoran Canyon.

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