Gold in Porphyry Copper Systems

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Chapter E

Gold in Porphyry Copper Systems

Gold in the Bingham District, Utah

By EDWIN W. TOOKER

Gold in the Butte District, Montana

By EDWIN W. TOOKER

Gold in the Ely (Robinson) Copper District, White Pine County, Nevada

By LAURENCE P. JAMES

The Tomboy-Minnie Gold Deposits at Copper Canyon, Lander County, Nevada

By TED G. THEODORE, STEPHEN S. HOWE,
and DAVID W. BLAKE

U.S. GEOLOGICAL SURVEY BULLETIN 1857

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Gold in Porphyry Copper Systems

Gold in the Bingham District, Utah

By Edwin W. Tooker

Abstract

The Bingham mining district, Utah, is a major United States producer of gold as a byproduct of copper and molybdenum sulfides dispersed in an intrusive quartz monzonite porphyry stock and in skarns in adjoining carbonate sedimentary rocks. The district has also produced substantial amounts of gold, silver, lead, and zinc in polymetallic veins and bedded replacements of carbonate-rich sedimentary rocks in and peripheral to the intrusive body. Mining of the gold-bearing lead-silver lodes and the gold placers began in 1863. Production from the porphyry deposit started in 1906; that from the skarn ores began in 1979. The average grade of dispersed gold is believed to be in the range of 0.31–0.62 grams (0.01–0.02 troy ounce) per ton; the grade of skarn gold is as high as 1.5 grams (0.045 ounce) per ton. The gold production from the Bingham district exceeds 603 metric tons (19.4 million troy ounces), and the estimated district's reserve of gold is well in excess of 505.6 metric tons. Sediment-hosted disseminated primary gold discovered recently in an area north of the Bingham open pit mine is expected to begin production in 1989. A grade of 2.4 grams per ton has been identified, and a reserve of 12.4 metric tons (400,000 ounces) has been announced.

The Bingham ore deposits occur mainly in the allochthonous folded upper plate of the Bingham nappe, one of the foreland Sevier thrust lobes that were emplaced from the southwest onto a basement promontory aligned with the east-west-trending Uinta-Cortez axial zone. This zone is the locus of a number of intrusive porphyry stocks, dikes, and sills, and extrusive rocks in western Utah. The main stratigraphic host is the Upper Pennsylvanian Bingham Mine Formation of the Oquirrh Group, which consists of cyclically interbedded medium- to thick-bedded silica- and carbonate-cemented quartzite, calcareous sandstone, and arenaceous, fossiliferous, cherty, argillaceous, and dense limestones. Prominent close-spaced northeast-trending faults, which resulted from tension by arching during thrust emplacement of the overturned Bingham syncline and an adjoining broad anticlinal fold, are the locus of the extensive porphyry and vein deposits in and peripheral to the stock.

The district is centered on the composite porphyritic and equigranular quartz monzonitic, hydrothermally altered, mineralized Bingham stock and associated later intrusive dikes and sills, and extrusive volcanic rocks. The ores are zoned about the central Bingham stock: The dispersed deposit has a central low-grade core containing magnetite, and successively a molybdenite zone low in copper, a bornite-chalcopyrite-gold higher-grade zone, a pyrite-chalcopyrite zone, a pyrite zone, and an outermost lead-zinc zone. The central porphyry ores were formed from hot (400–600 °C), highly saline, mantle-derived hydrothermal fluids under a pressure of about 800 bars. Rock shattering by boiling produced breccia pipes. The outer vein and replacement deposits in the sedimentary sequence formed at lower temperatures (about 300 °C) as a result of mixing of magmatic and meteoric waters. The dispersed gold occurs mainly in a network of close-spaced thin fractures in the central porphyry body; locally the gold is disseminated in the altered fracture blocks in the copper-rich zone as the native metal and as telluride minerals. Gold reportedly was enriched in the upper parts of the porphyry intrusion. Skarn gold deposits also are associated with high-grade copper ores. Polymetallic vein gold deposits occur as siliceous gold-silver fissures; gold is associated with copper, lead, and zinc ores, generally in enriched ore shoots. Native gold is rare in the peripheral lead-zinc ores. Replacement gold also occurs along bedding fissure zones in small local shoots. Native(?) gold is disseminated in altered carbonate-rich (dolomitic) rocks at the neighboring Barneys Canyon deposit.

Manuscript approved for publication August 1, 1989.

INTRODUCTION

The Bingham mining district, one of the major producers of gold in the United States, is located mainly in the headwaters of Bingham Canyon on the east side of the Oquirrh Mountains, about 32 km southwest of Salt Lake City, Utah (fig. E1). The Bingham (originally West Mountain) district broadly includes the open pit copper mine centered on a quartz monzonitic composite porphyritic and equigranular intrusion in Bingham Canyon, the underground skarn and polymetallic base and precious metal vein and replacement deposits in the carbonate rocks peripheral to the intrusion, and the now exhausted placers. Sediment-hosted disseminated gold has been discovered recently by Kennecott (now known as BP Minerals America) in the greater Bingham area. This richly mineralized Bingham mining region covers an area of more than 16 km^2 and includes parts of several adjacent drainage basins.

Early development of the district was hampered by its remote location and by economic conditions. The discovery of the lead-silver lodes by the Bingham brothers was reported in local newspapers in 1860.

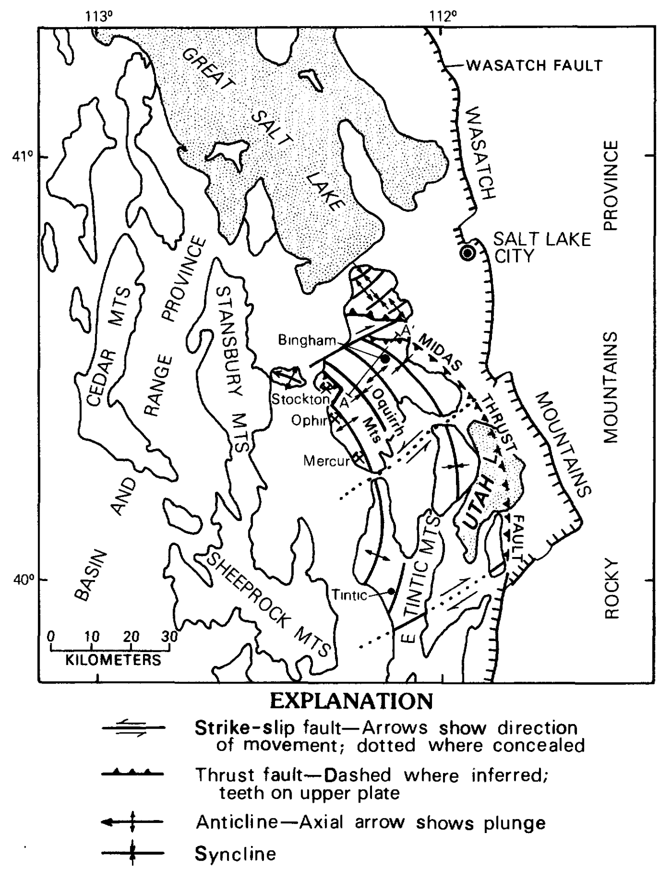

Figure E1. Location of Bingham mining district and other mining districts in the Oquirrh Mountains area, Utah, and of section *A–A'* of figure E4.

George Ogilvie "rediscovered" the deposit in 1863, and, in collaboration with Col. P.E. Connor and soldiers of the U.S. Army stationed in the Utah territory, located the first lode mining claims and organized the West Mountain mining district. Gold placers in thick gravels along Bingham Creek were discovered in 1864. The original mining claim was patented in 1877. In a review of the early history of the district, James (1978) noted that early mining was sporadic owing to transportation and smelting difficulties. The advent of the railroad to Bingham Canyon in 1873 encouraged mining briefly, but the relatively low prices of lead, zinc, and silver of that period discouraged mining activities for a time. By 1896 near-surface high-grade copper sulfide lodes were being mined underground, and until 1971 gold continued to be an important byproduct of the copper-lead-zinc-silver vein and manto replacement deposits peripheral to the intrusion (Hunt, 1924; Rubright and Hart, 1968; U.S. Bureau of Mines Minerals Yearbooks, 1961–1981).

After 1900, the technology was developed to mine and recover low-grade copper dispersed in porphyritic rocks and enclosing sedimentary rocks, and necessary smelters were built nearby. In 1906 open pit mining for copper began and byproduct gold was recovered during milling of the ore. By 1911 the small mining enterprises (once numbering 21) were beginning to be consolidated, ultimately to form three major operations; in 1970, when UV Industries, Inc. (formerly U.S. Smelting, Refining, and Mining Co.) ceased operations, that number was reduced to two, Kennecott and The Anaconda Minerals Company. In the mid-1970's development was considered feasible for the copper and the byproduct gold in skarn ores in the metamorphosed carbonate rocks adjacent to the northwestern side of the Bingham stock, underlying the Carr Fork and main Bingham Canyon areas (Atkinson and Einaudi, 1978). Limited production was begun at Carr Fork in 1979; however, low prices and a world oversupply of copper temporarily discouraged production of byproduct gold from the skarn ores. Continued unfavorable economic conditions forced the close of Kennecott's Utah Copper open pit mine in 1985, which was the last remaining operation in the district. Although down, the Bingham Canyon mine was not out, and limited production resumed in 1987 concurrent with a massive modernization program for its mining and milling facilities (Skillings Mining Review, 1985). In 1986, Kennecott, then a subsidiary of SOHIO (Standard Oil Company, 1986), announced the discovery of a substantial deposit of low-grade sediment-hosted disseminated gold in Barneys Canyon, an area about 6.5 km north of the open pit mine (see fig. E7).

The purpose of this report is to consolidate and review the scattered published data on the occurrence and magnitude of the often-overlooked several overlapping types of gold deposition in the Bingham district.

Specific details on the geologic environment and resources of byproduct gold in the dispersed ore body have not been readily available until recently, and some conclusions may be inferred from other scattered published records. The gold deposits at Bingham are unique with respect to their size, but are not unlike subvolcanic porphyritic granitic pluton-centered vein and replacement deposits in the Cordilleran region and beyond. The Ely, Nevada, and Battle Mountain, Nevada, deposits (described elsewhere in this chapter) are, in part, comparable deposit types.

I am pleased to acknowledge the important geologic contributions by staffs of Kennecott, the Anaconda Minerals Company, and U.V. Industries during the past 125 years, which form an important basis for this report. Critical reviews by A. Jaren Swensen, Kennecott, Bingham Canyon, Utah, and R.D. Rubright, West Jordan, Utah, are appreciated; however, geologic interpretations herein remain my responsibility. The contributions of U.S. Geological Survey personnel and colleagues, particularly MacKenzie Gordon, Jr., R.C. Douglass, and W.J. Moore in geochronology and stratigraphic interpretation of formational units, are also gratefully acknowledged.

PRODUCTION AND RESERVES

Until recently gold production and reserve data for the Bingham district could only be estimated because of proprietary restrictions on their publication. About 603 metric tons (19.4 million oz) of gold have been produced mainly from four types of deposits (fig. E2). About 2.3 metric tons (75,000 oz) of placer gold was won from the gravels in Bingham Canyon creek and its tributaries (table E1 and fig. E3) in the early days of the district. The first four decades of production from polymetallic vein and replacement deposits averaged nearly 0.28 metric ton (9,000 oz) per year (table E2). Grade and tonnage of typical ores mined and the gold recovery from various types of vein and replacement ores are shown in table E3. More than 75 metric tons (2.4 million oz) of gold was produced as a byproduct of copper-lead-zinc-silver ores in the vein and replacement deposits in carbonate and intrusive rocks ringing the porphyritic stock; the last of these mines was closed in 1971. The advent of mining of the dispersed copper and molybdenum ores resulted in a substantial increase in annual production of gold from the district (table E2), and for many years this byproduct source has been the second most abundant domestic source of gold, whose production totals nearly 526 metric tons (16.9 million oz). In the three years (1982–1984) preceding closing of the Utah Copper mine in 1985, dispersed gold production averaged 0.179 metric tons (5,755 oz), as well as 163,000 metric tons copper, 74.6 metric tons (2.4 million oz) silver, and 1,800 metric tons molybdenum metal per year (British Petroleum Company, 1986). In addition, byproduct platinum group metals, uranium,

Table E1. Production and average grade of gold deposits, Bingham mining district, Utah

Type of ore	Years	Production of gold (1000 g)	(1000 oz)	Average grade (oz Au/ton)	References
Placer	1864-1935	2,333	75	--	Johnson (1973).
Dispersed in porphyry.	1904-1961	351,468	11,300	0.010	Stowe (1975), Hammond (1961), and U.S. Bureau of Mines (1961-1981).
	1962-1980	155,517	5,000	--	
	1982-1986	19,160	616	0.013	British Petroleum (1986).
Total[1]----		528,478	16,990		
Vein and replacement peripheral to porphyry.	1863-1964	74,648	2,400	0.02	Rubright and Hart (1968).
	1965-1971	not available			
Total----		>74,648	>2,400		
Skarn in limestone	1979-1981[2]	1,244	40	0.05-0.03	Atkinson and Einaudi (1978), W.J. Garmoe (oral commun., 1982, 1987).
GRAND TOTAL----		>604,370	>19,430		

[1]Reserves of 335.04 metric tons (10.8 million oz) gold inferred minable by open pit in Bingham Canyon deposit.

[2]Production did not reach planned level before shut down; reserves of about 143 metric tons (4.6 million oz) of gold are inferred in the Carr Fork and Bingham Canyon skarn deposits.

Table E2. Gold production, Bingham district (Butler, 1920)

Years	Production (oz Au)	Average recovery (oz/year)	Principal ores mined
1865-1904	338,000	8,700	Vein and replacement ores.
1904-1917	1,177,000	90,500	Dispersed, vein, and replacement ores.

selenium, tellurium, silver, and rhenium were also recovered. The latest forecast estimate for production, following plant modernization in late 1988, is 70,000 short tons of ore per day, from which 168,000 short tons of refined copper, 8.087 metric tons (260,000 oz) of gold, 62.207 metric tons (2.0 million oz) of silver, and 3,600 metric tons of molybdenum per year will be produced (Mining Journal, 1987). Skarn gold, also a byproduct of copper-molybdenum-silver mining, amounted to 1.244 metric tons (40,000 oz) during its initial 3 years (1978–1981) of production at the Carr Fork deposit, prior to its premature closure in 1982 (Cameron and Garmoe, 1987).

A large reserve of gold in the Bingham district, until recently in large part undisclosed, is now estimated to be at least 505.6 metric tons (16.3 million oz). Placers were considered exhausted in the early 1940's (Johnson, 1973). Byproduct gold resources in the United States mine are considered minimal, but gold reserves in the Lark mine were calculated to be at least 0.653 metric ton (21,000 oz) when these mines were closed (R.D. Rubright, written commun., 1983). Reserves of byproduct dispersed gold in the Utah Copper ore body are 335 metric tons (10.8 million oz). The ores also include 4.9 million metric tons copper, 2,317.36 metric tons (75.5 million oz) silver, and 350,000 metric tons molybdenum (British Petroleum Company, 1986, p. 112). Skarn ore reserves in the Carr Fork mine are estimated to be about 31 metric tons (1 million oz) gold (Cameron and Garmoe, 1987); a larger reserve present in the underground mine to be developed by BP Minerals America, which includes a northward extension of the Carr Fork deposits (fig. E3), is estimated at 127 metric tons (4,127,500 oz) gold, 2.28 million metric tons copper, 1,694 metric tons (54,462,000 oz) silver, and 243,000 metric tons molybdenum (British Petroleum Co., 1986, p. 113). A reserve of at least 12.441 metric tons (400,000 oz) of gold was reported in an announcement of the discovery of a carbonate-hosted disseminated gold deposit in the Barneys Canyon area (Standard Oil Co., 1986, p. 40; British Petroleum Co., 1986, p. 114). Additional drilling underway and projected by BP Minerals America and American Barrick Resources (USA) undoubtedly will increase this reserve.

GEOLOGIC SETTING

In the Oquirrh Mountains thick sections of miogeoclinal carbonate-rich sedimentary rocks of late Paleozoic age make up the folded upper plates of three thrust fault nappes that were emplaced over the Precambrian craton platform during the Sevier orogeny of Cretaceous age (Tooker, 1983). These rocks were intruded and altered by subvolcanic granitoid intrusions of Tertiary age (Moore, 1973b). The structural and geochemical environment at Bingham became the site of deposition of gold, silver, and base metals during the late stages of this igneous event. In late Tertiary time, tensional listric faults in the eastern Basin and Range province tilted the Oquirrh Mountain block eastward, and exposed rocks subsequently eroded to the present surface.

Table E3. Gold produced from types of ore mined, Bingham district (from Butler, 1920)

Years	Types of ore	Average ore mined (tons/year)	Average gold recovered (oz/ton)	Average gold production (oz/year)
1903-1905, 1908-1917	Siliceous ore	2,300	0.2	460
1903-1917	Copper ore	524,666	.09	47,200
1903-1917	Lead ore	77,267	.08	6,181
1907-1913, 1916	Copper-lead ore[1]	207	.4	83
1910-1911	Lead-zinc ore	468	.07	33
1912-1913	Zinc	3,931	.03	118

[1]Includes rich ore shoots.

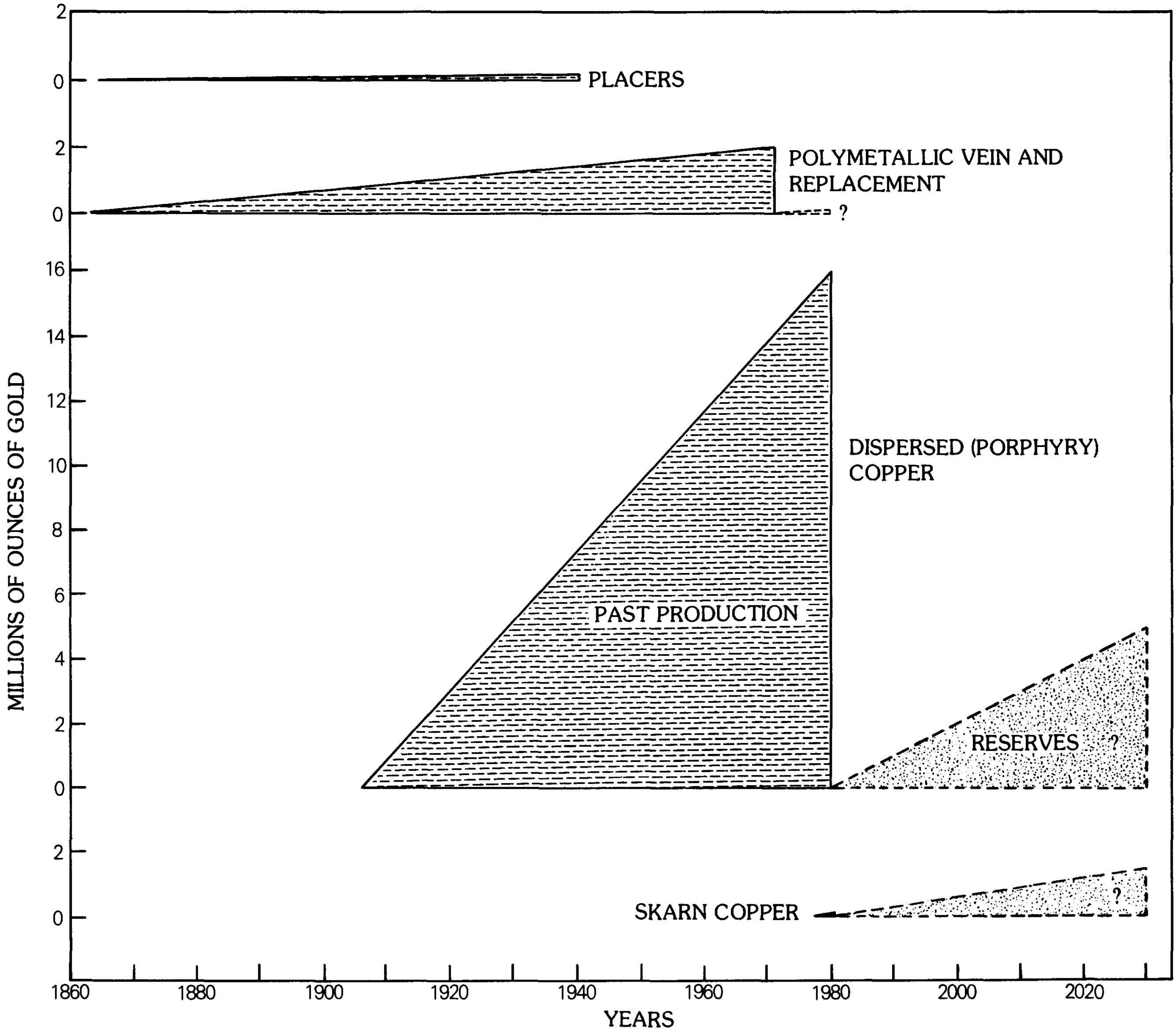

Figure E2. Comparison of the relative cumulative amounts of gold produced from the four types of gold deposits (solid line) during their respective eras of production, and estimates of available (or inferred) reserves, if any, remaining (dashed).

The stratigraphic and structural features of the sedimentary hosts, the petrologic and geochemical attributes of intrusive rocks, and the composition of accompanying hydrothermal solutions are detailed in reports beginning with Boutwell's classic report (1905). This paper was followed by a number of geologic reports resulting from the 1919–1920 Apex lawsuits (Beeson, 1917; Hunt, 1924; Peterson, 1924; and Winchell, 1924), and more recent studies sponsored by the mining companies (Hunt and Peacock, 1950; James, Smith, and Bray, 1961; James, Smith, and Welsh, 1961; Peters and others, 1966; Rubright and Hart, 1968; John, 1978; Lanier, John, and others, 1978; Warnaars and others, 1978; and Atkinson and Einaudi, 1978).

Stratigraphy

The productive ore deposits at Bingham occur in allochthonous miogeoclinal cratonal (shelf) rocks including the upper part of the Butterfield Peaks Formation and the Bingham Mine Formation in the Bingham nappe, and the herein informally designated Flood Canyon and Dry Fork units in the Pass Canyon nappe. Strata on the Bingham plate comprise about 2,230 m of sedimentary rocks of Pennsylvanian (Desmoinesian to Virgilian) age (figs. E4 and E5) that have moved an unknown distance northeastward as a thrust nappe (Tooker, 1983). The Flood Canyon and Dry Fork

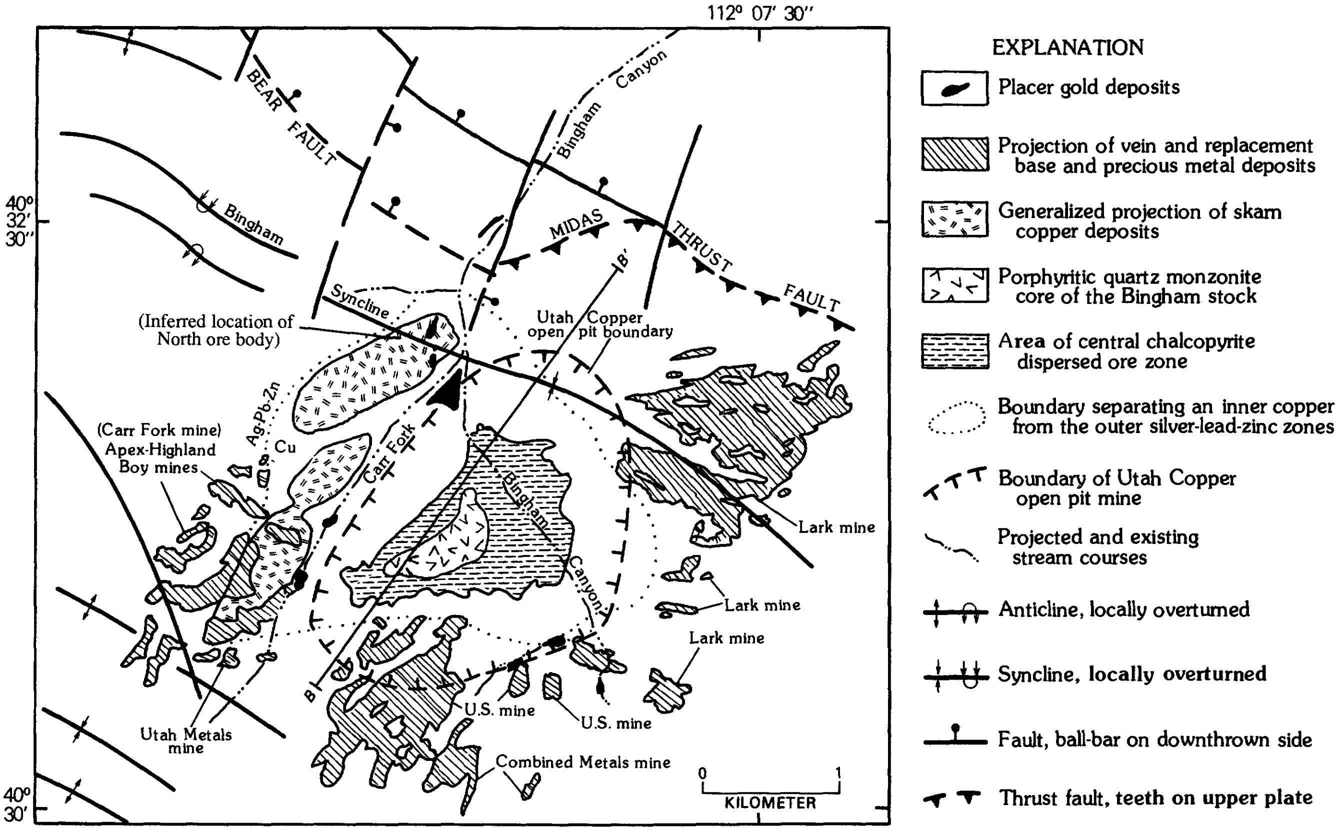

Figure E3. Surface projections of dispersed, vein and replacement, skarn, and placer ore bodies in the Bingham district, Utah (compiled from Rubright and Hart, 1968; Atkinson and Einaudi, 1978; and Johnson, 1973). Approximate line of section *B–B′* of figure E9.

units of Early Permian (Wolfcampian) age originally were thrust generally east on the Pass Canyon nappe plate prior to emplacement of the Bingham plate. The Pass Canyon nappe and Flood Canyon unit are named for prominent canyons on the west side of the range that empty into Tooele Valley in sections 8 and 6, respectively, T. 3 S., R. 3 W. The Dry Fork unit is named for exposures in Dry Fork, a tributary that empties into Bingham Canyon in sec. 13, T. 3 S., R. 3 W.

The stratigraphic section in the Bingham nappe is composed of the two uppermost formational units in the Oquirrh Group. The Butterfield Peaks Formation (figs. E4–E6) contains a cyclically interbedded predominantly carbonate sequence of calcareous quartzite, orthoquartzite, calcareous sandstone, and fossiliferous, arenaceous, cherty, argillaceous, and fine-grained dense limestone beds. The Clipper Ridge Member, the lower member of the Bingham Mine Formation, is composed predominantly of cyclically interbedded orthoquartzite, calcareous quartzite, and quartzose sandstone interbedded with several thick limestone layers. The Markham Peak Member, the upper member of the Bingham Mine Formation, is composed of orthoquartzite, calcareous quartzite, calcareous sandstone, and a few thin fusulinid-bearing arenaceous limestone units (Swensen, 1975; Tooker and Roberts, 1970).[1] Thick limestone units in the lower part of the Clipper Ridge Member and thinner beds in the Markham Peak Member are the principal units that were faulted, cut by stocks, and altered to skarns and (or) mineralized adjacent to the stocks.

The Barneys Canyon disseminated gold prospect occurs in tightly folded, faulted, and sheared rocks of the allochthonous Flood Canyon unit of the Pass Canyon nappe in sec. 34, T. 2 S., R. 3 W. This area, which contains a number of small old mines and prospects, is a few kilometers north of the open pit mine porphyry ore bodies. The host rocks of Permian age consist of a series of light-brown to reddish-brown calcareous quartzite beds at the base followed upward by light-gray or tan calcareous sandstone, intraformational breccia and interbedded arenaceous limestone, dolomite, dolomitic

[1]The top 370 m of the upper member includes strata described by Tooker and Roberts (1970) as the upper part of the Markham Peak Member, Bingham Mine Formation, and by James, Smith and Welsh (1961) as the lower part of the Curry Peak Formation of James, Smith, and Welsh (1961) and of Swensen (1975).

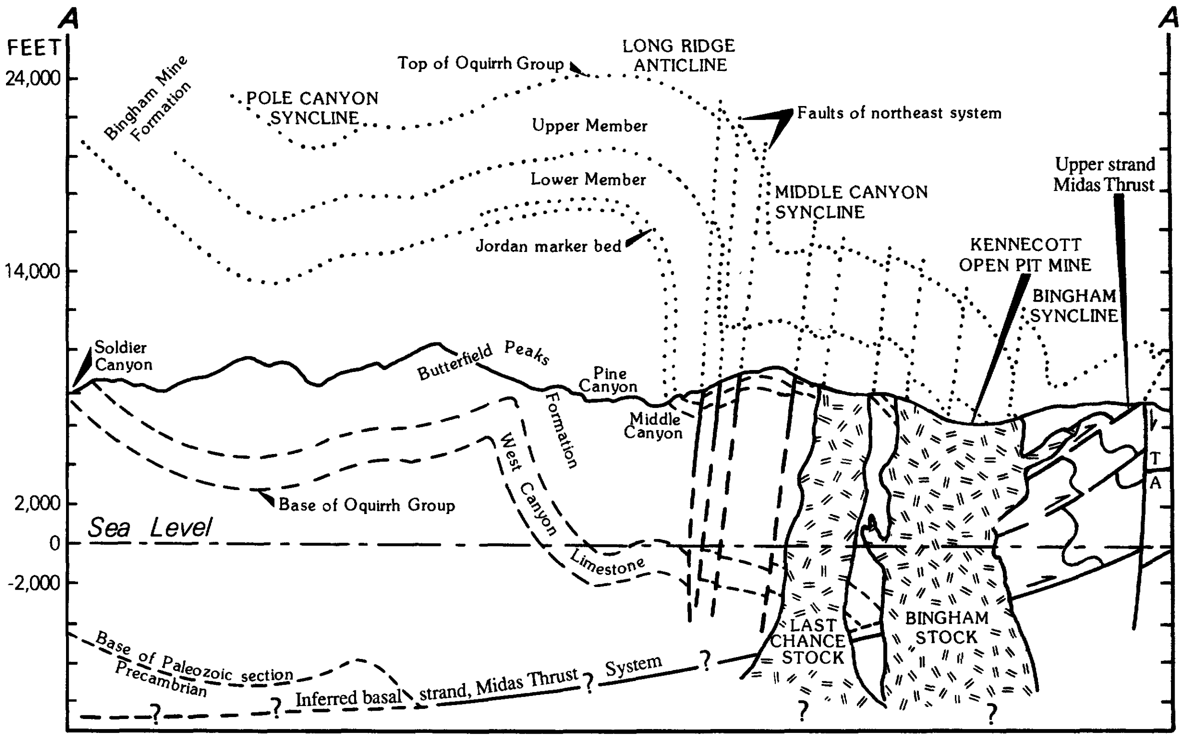

Figure E4. Northeast-trending cross section *A–A'*, Oquirrh Mountains, from Soldier Canyon to the Bingham mining district, showing characteristic fold deformation in the Bingham allochthon (modified from Tooker, 1971). Location of section, figure E1.

limestone, calcareous sandstone, and quartzitic sandstone. Sedimentary rocks are cut by altered porphyry dikes.

Structure

A series of structural events preceding the intrusion of igneous rocks prepared this area for the formation of the mineral deposits at Bingham (Tooker, 1983). The district overlies an inferred buried east-west cratonal lineament or suture zone (Uinta-Cortez axis of Roberts and others, 1965), which, locally along its length, has been a site for occasional uplift during Phanerozoic time (Tooker, 1971); it is also the locus of a family of Tertiary granitic intrusions (Moore and McKee, 1983) that cut Paleozoic and Mesozoic miogeoclinal strata overlying the Precambrian craton platform rocks. A foreland craton buttress against which the Sevier overthrusts of Cretaceous age were obstructed, deflected, deformed, and halted (Tooker, 1983) consisted of an uplifted promontory along the Uinta-Cortez lineament in the vicinity of Salt Lake City. At least three Sevier thrust nappe lobes converged on the buttress located east of the northern Oquirrh Mountains (fig. E7; Tooker and Roberts, 1988). The main gold-bearing ore deposits occur in the Bingham nappe plate, the second lobe to be emplaced from the southwest along the Midas thrust fault[2] system. The thrust system produced asymmetrical to locally overturned folds in an arc convex to the northeast, as shown in figure E6. Segments of folds in the Bingham area locally are overturned to the northeast, and where the fold curvature is tightest, bedding shears and small intraplate thrusts were formed locally. Tension within the arc produced a prominent conjugate set of steeply dipping northeast- and northwest-trending cross faults. Vein, replacement, and skarn deposits occur mainly near these cross, thrust, or bedding faults, and outward from the intrusions along reactive beds.

The Last Chance and Bingham stocks, and associated plugs and dikes, were intruded into structurally disrupted adjoining parts of the Bingham and Pass Canyon nappes. Intrusion of the stocks provided local dilation of the northeast-trending fault set. The

[2]The local versus regional characterization of the Midas thrust, as defined originally in mapping by James, Smith, and Welsh (1961), and the Midas thrust system, required by the geometry implicit in regional mapping by Tooker and Roberts (1988), remains unresolved, pending release of more detailed underground data. It seems clear, however, that the original fault structure shown on the map is a minor imbrication in the upper plate of an as yet unexposed more fundamental structure, for which I tentatively retain the term basal thrust of the Midas system in this report.

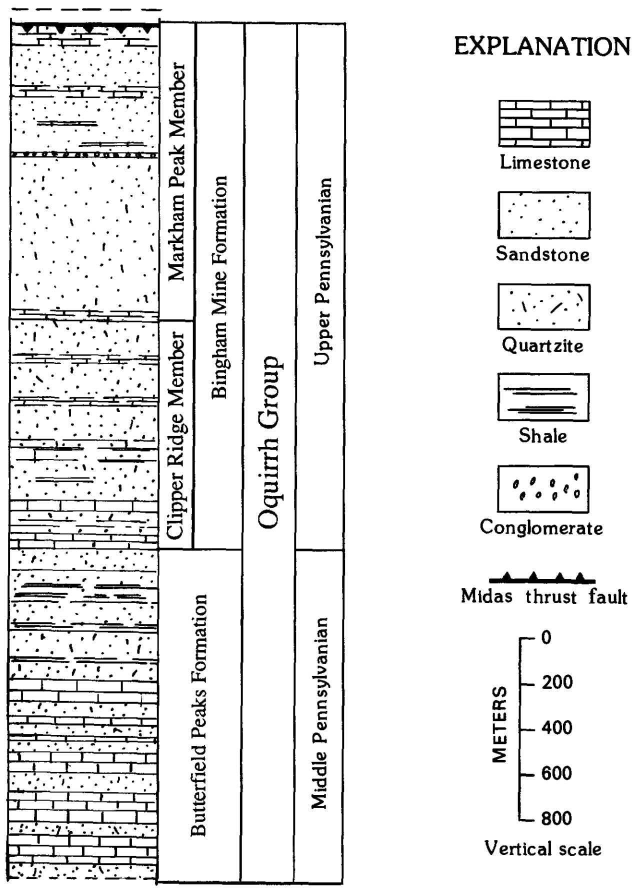

Figure E5. Paleozoic rocks exposed in the Bingham allochthon in the Bingham district (modified from Swensen, 1975).

disseminated gold prospect occurs along a northeast-trending fault in rocks of the Pass Canyon nappe and is associated with granitic dike rocks.

East-west extension of the region west of the Wasatch Range, in what is now called the Great Basin, produced listric faults that subsequently tilted the Oquirrh Mountains block as much as 25° to the east (Atkinson and Einaudi, 1978). Many of these faults, particularly those on the west side of the range, resulted from local reactivation of the earlier conjugate fault system, producing an irregular saw-tooth faulted range front.

Intrusive Rocks

The Bingham district is centered on a composite, hydrothermally altered and mineralized pluton, the Bingham stock, its unaltered neighbor, the Last Chance stock, and associated later intrusive and extrusive bodies (figs. E3, E6; Lanier, Raab, and others, 1978). Major intrusive phases are composed of equigranular monzonite and quartz monzonite porphyry (table E4) (Moore, 1973b;

Table E4. Average modal composition, in percent, of Bingham stock intrusives (Lanier, John, and others, 1978)

Monzonite[1]		Quartz monzonite porphyry[2]	
Potassium feldspar	30	Potassium feldspar	32
Plagioclase	33	Plagioclase	32
Quartz	7	Quartz	22
Augite	11	Mafic minerals (mainly hornblende and biotite)	14
Biotite	8		
Amphibole	7		
Magnetite	2		
Accessory minerals	2		
Total	100	Total	100

[1]Dark gray, fine grained, equigranular.

[2]Light gray, coarse grained, 50 percent phenocrysts, mostly altered.

Lanier, John, and others, 1978). The center of mineralization was the porphyritic quartz monzonite intrusion within the generally equigranular Bingham stock. The adjoining unaltered Last Chance stock and smaller satellitic pluton bodies may be connected at depth. A latite porphyry dike swarm and thin younger quartz latite porphyry dikes and plugs cut the stocks generally along the northeast trend of cross faults.

Pre-ore mostly barren breccia pipes (not shown) of widely varied sizes (as much as 180 m diameter) occur on the south and east sides of the Bingham stock (Rubright and Hart, 1968). They are nearly vertical, and may penetrate to depths of as much as 1,220 m. The pipes are composed of rounded to angular fresh and altered fragments of most rocks found in the district in a matrix of silica and porphyry.

Alteration

A zoned hydrothermal alteration pattern (fig. E8) occurs in the intrusive and sedimentary rocks around the extremely fractured central quartz monzonite porphyry phase of the Bingham stock (Moore and Nash, 1974; Lanier, Raab, and others, 1978; Atkinson and Einaudi, 1978). Rock alteration resulted both from high-temperature, high-salinity fluids accompanying the late stages of the intrusion of the equigranular quartz monzonitic (Bingham) stock, and from peripheral low-temperature, low-salinity fluids related to the influx and mixing of meteoric and magmatic waters. The mineralogic consequences also vary with the composition of the fresh host rocks.

Wallrock alteration and sulfide mineral zones extend outward from the quartz monzonite intrusion along its contacts, in fracture zones in the sedimentary and intrusive rocks, and in crosscutting fissures. Two prominent zones of quartz monzonite alteration

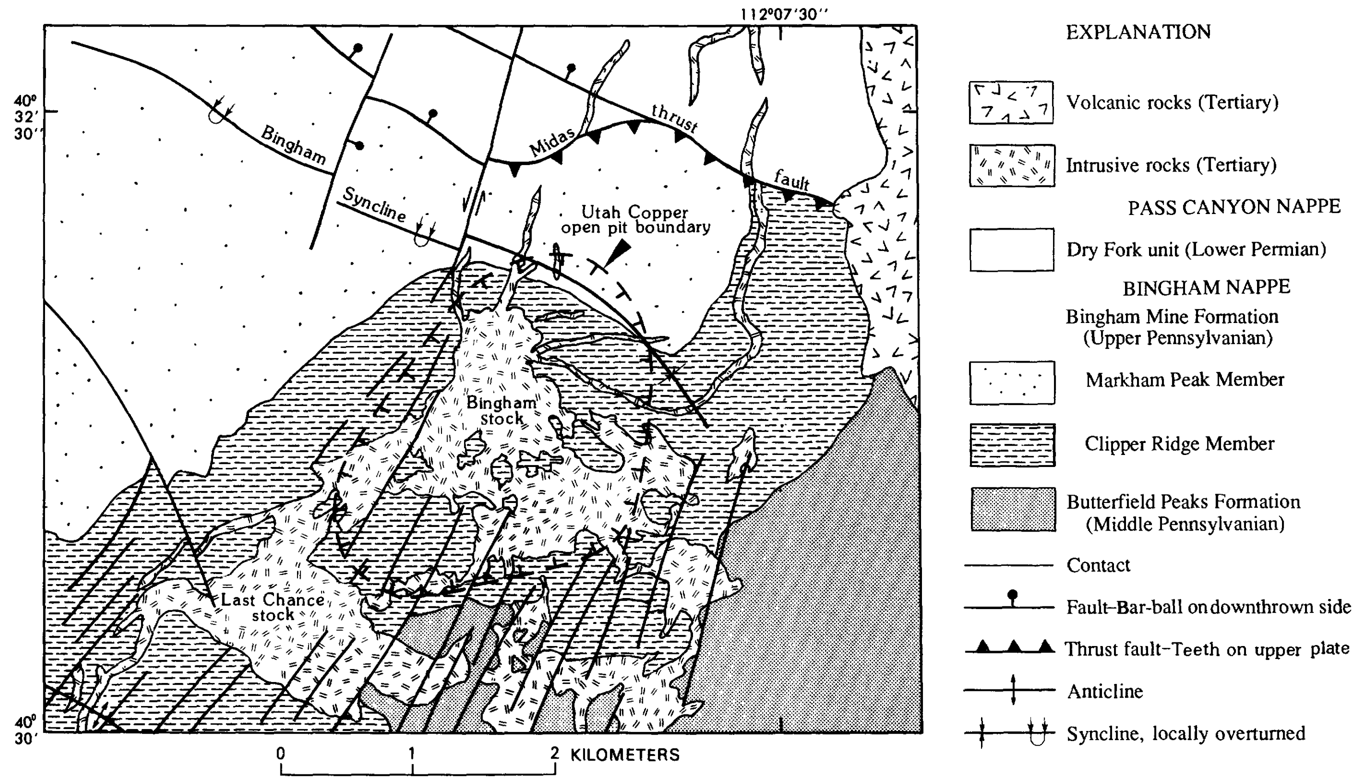

Figure E6. General geologic setting of the Bingham mining district (modified from Tooker, 1971).

recognized include a central quartz-orthoclase-phlogopite (hydrothermal biotite) potassium silicate zone, and an outer actinolite-chlorite-(epidote) propylitic alteration zone (Lanier, Raab, and others, 1978). A superposed zone of pervasive sericitic alteration of the biotitized intrusion along a northeast-trending zone in the northern part of the district is not part of the concentric alteration pattern (Moore, 1978).

Atkinson and Einaudi (1978) recognized three stages in the alteration of the sedimentary rocks. An early contact metasomatism of calcareous quartzite and thin silty limestone to diopside, and of thick cherty limestone to wollastonite and garnet, was accompanied by deposition of trace sulfides. A main-stage alteration of diopside in quartzite to actinolite, and garnetization of wollastonite-bearing marble in limestones occurred simultaneously with the potassic alteration in the intrusion. These skarn zones host copper sulfides, galena, sphalerite, and molybdenite. The late-stage assemblage of pyrite, chlorite, smectite, sericite, and calcite replaced the calc-silicate minerals. Lead-zinc and gold ores formed during this stage, accompanied by arsenic-bearing minerals. This late stage was contemporaneous with the sericite-pyrite alteration in the monzonite. On the basis of alteration mineral assemblages in sedimentary rocks peripheral to the central intrusion, Hunt (1957) inferred that much of the lead-zinc-silver mineralization was associated with a later hydrogen metasomatism that produced sericite in igneous rocks, clay minerals in calc-silicate sedimentary rocks, and carbonate-silica minerals in limestone.

Age of Ore Formation

The deposition of gold and associated base metals took place during several pulses of hydrothermal activity over a span of about 1 m.y. (table E5), following the intrusion of the equigranular monzonite at 39.8 Ma (Warnaars and others, 1978; Moore and Lanphere, 1971; Moore, 1973a). The occurrence of free gold intimately associated with the copper minerals chalcopyrite and tetrahedrite (Peters and others, 1966; Cameron and Garmoe, 1983), and fine-grained native vein gold (Boutwell, 1905; Rubright and Hart, 1968) suggests that early gold deposition may have been followed by subsequent redistribution or reintroduction of this metal. Igneous activity in and adjacent to the district at Shaggy Peak, about 3,500 m to the southeast (not shown), shows that this activity continued over a span of 6 m.y. (table E5). The age of disseminated gold in Barneys Canyon remains to be determined, but that gold also is presumed to have been deposited during a low-temperature late phase.

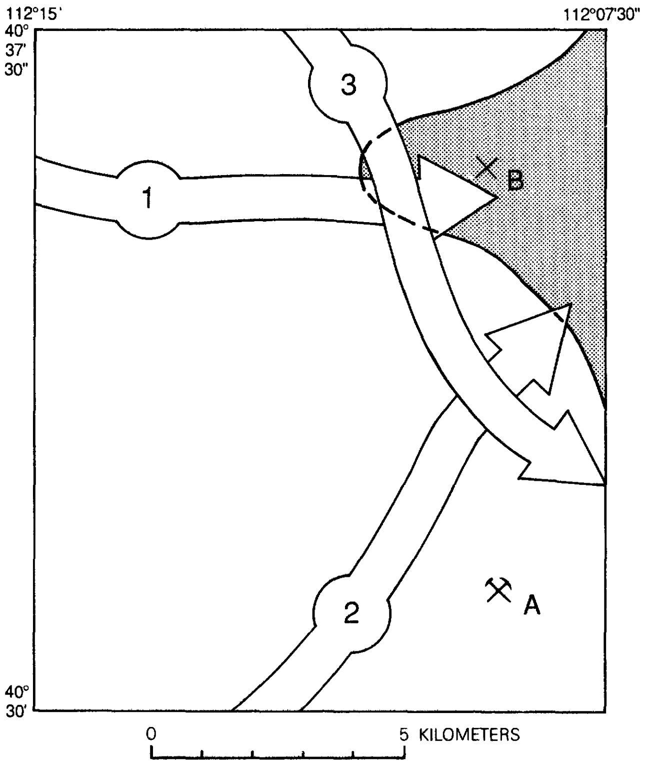

Figure E7. Sketch showing inferred paths of Sevier foreland thrust nappe movement against the craton promontory (shaded) in the Bingham Canyon quadrangle. 1, Pass Canyon nappe; 2, Bingham nappe; 3, Rogers Canyon nappe. Location of the area of Barneys Canyon disseminated prospect (B) north of the present Utah Copper open-pit mine (A) is shown.

Metallization Environment

The characteristics of hydrothermal fluids that altered the host rocks and deposited metals are inferred from mineralogic associations and the chemical and isotopic composition of fluid inclusions in the rocks (Field and Moore, 1971; Moore and Nash, 1974; Bowman and others, 1987). These data indicate that high temperatures (400–600 °C) and highly saline solutions were present in the Bingham stock and adjacent sedimentary rocks, and that the temperature decreased to 300 °C in the peripheral deposits (Roedder, 1971). Sulfur isotopic data suggest that these high-temperature solutions were derived from a common mantle source (Field and Moore, 1971). An estimate of fluid pressures of about 800 bars by Moore and Nash (1974) corresponds to a lithostatic load of about 3 km. The fluid inclusions as well as the breccia pipes provide evidence of shattering of the rocks and boiling. An increase in mixing of hydrothermal solutions with meteoric water occurred as the rocks cooled during probably more than one episode of recharge by the hot solutions (Field and Moore, 1971; Bowman and others, 1987) in a near-surface environment. Mineralization occurred mainly before the emplacement of the quartz latite porphyry, which is poorly fractured and weakly altered and mineralized only where it cuts strongly fractured and mineralized monzonite. The late-mineralized veins may represent the waning final stages of hydrothermal activity in the peripheral parts of the system. The continuity of magmatic and hydrothermal conditions indicated by sulfur and lead isotopic data (Field and Moore, 1971; Stacey and others, 1967) suggests that potassic alteration and initial copper sulfide mineralization were accomplished by highly saline high-temperature solutions. The lead in these solutions was derived from the mixing of radiogenic leads associated in Tertiary intrusive magma and crustal basement rocks (Stacey and others, 1968).

Table E5. Geochronology of intrusives, alteration, mineral deposition, and volcanic rocks (Warnaars and others, 1978)

Rock units	Age (Ma)
Shaggy Peak Rhyolite	35.0-32.8
Quartz latite porphyry	38.8±0.3 (average)
Porphyry copper mineralization	39.8-38.8
Quartz monzonite porphyry	38.8
Monzonite (Last Chance and Bingham stocks)	39.8±0.4

GOLD DEPOSITS IN THE BINGHAM DISTRICT

Gold occurs as an important byproduct in three main types of primary (and possibly in part remobilized) dispersed porphyry, skarn, and vein and replacement deposits. The areal distribution of these deposits, shown in figure E3, and their relations to the sulfide mineral zones centered on the mineralized Bingham intrusion (fig. E9) support a cogenetic relationship. Sulfide minerals, with which the gold is associated, are distributed in concentric rings (fig. E3) or in inverted cup-shaped zones (see cross section—fig. E9) centered on or draped over the central porphyritic quartz monzonite phase of the Bingham stock (John, 1978). The general zoning of sulfide minerals is: (1) a low-grade core containing magnetite and less than 0.5 percent sulfides; (2) a bordering molybdenite zone that is low in copper but grades outward into: (3) a bornite-chalcopyrite high-grade copper-ore zone; (4) a pyrite-chalcopyrite zone; (5) a pyrite zone; and (6) an outermost lead-zinc zone. Mineralization was most intense in the upper parts of the intrusion, where fracturing was greatest. Mineralization also occurred farther from the stock, however, along bedding in limestones, at contacts of the stock, and in

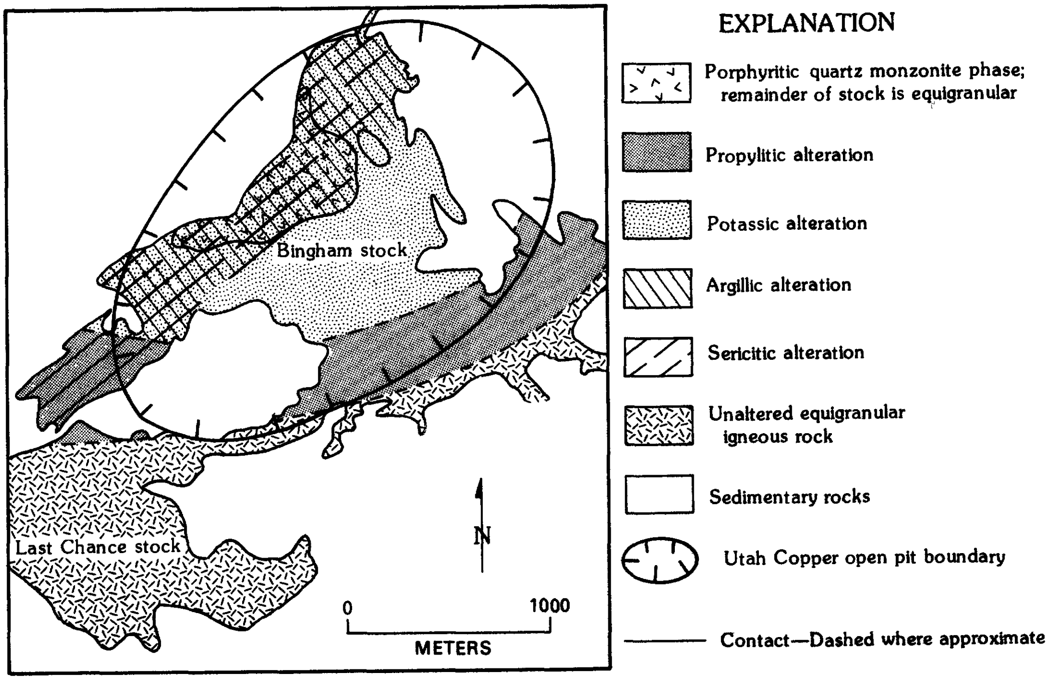

Figure E8. Plan map showing distribution of types of silicate alteration of intrusive rocks at Bingham (modified from Lanier, John, and others, 1978; and Moore and Nash, 1974).

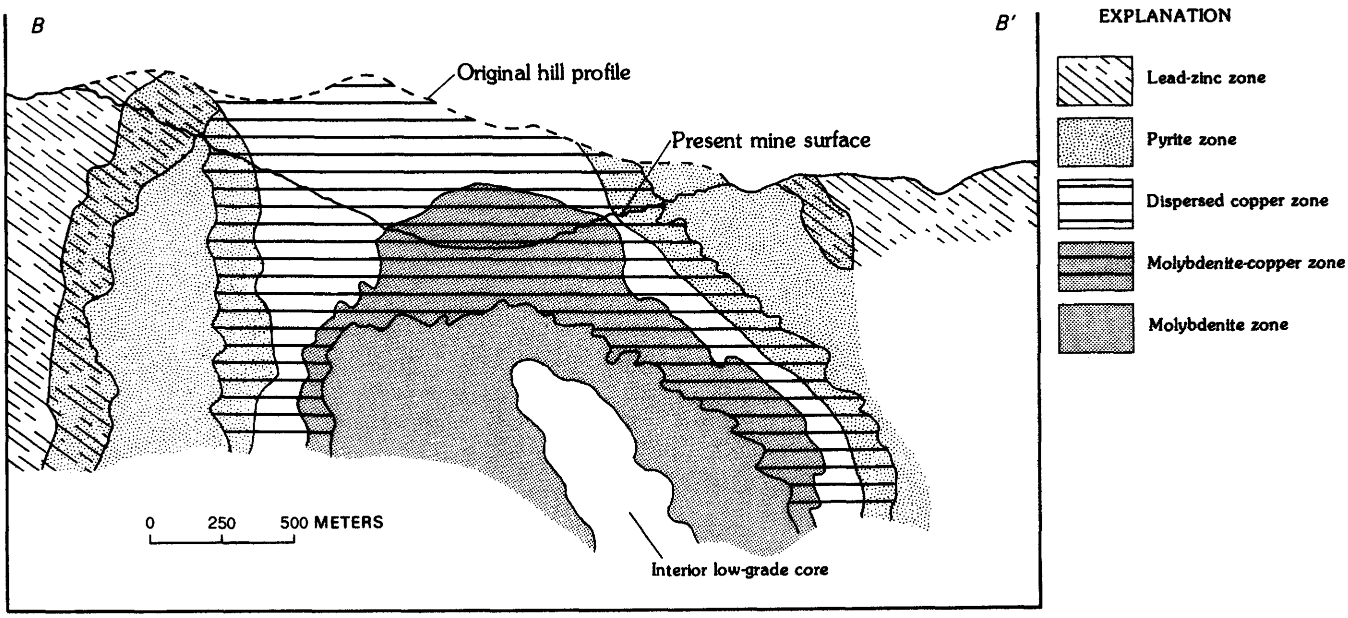

Figure E9. North-south cross section *B–B'* through the BP Minerals America (Kennecott) deposit in the Bingham district showing distribution of host rocks and sulfide mineral zones (modified from John, 1978). Location of section, figure E3.

cross-fracture systems in the sedimentary rocks and Last Chance stock, as indicated in figure E3. The amounts of base and precious metals recovered in these zones are shown in table E6. Studies of the newly recognized disseminated gold have not progressed sufficiently to determine whether they are genetically related to the central intrusive system.

Dispersed Porphyry Gold

Approximately 75 percent of the dispersed byproduct gold in the copper zone occurs in the shattered porphyritic and equigranular monzonite intrusive rocks of the Bingham stock in the core of the district; the remainder occurs in the adjoining mineralized altered

Table E6. Amount of base and precious metals recovered in vein and replacement ores through 1964 compared with that in dispersed intrusive ores

[Values in millions of units; vein and replacement ores from Rubright and Hart, 1968; ores dispersed in intrusives as approximated from values by Hammond, 1961]

	Gold (oz)	Silver (oz)	Copper (lbs)
Vein and replacement ores	2.4	136.0	814.5
Ores dispersed in intrusives	8.6	69.0	15,049.1
	Lead (lbs)	**Zinc (lbs)**	**Molybdenum (lbs)**
Vein and replacement ores	4,180.0	1,709.0	--
Ores dispersed in intrusives	--	--	451.1

Table E7. Grades of byproduct gold in nonporphyry ores, 1909–1946 (Hunt and Peacock, 1950)

Types of ore	Grade Au (oz/ton)	Production Au (oz)
Lead ore	0.065	232,000
Lead-zinc	.062	607,000
Lead-(copper)-zinc	.037	8,000
Gold-silver siliceous	.135	168,000
Copper ores (excludes surface mines)	.072	534,000
Total		1,549,000

quartzite and carbonate sedimentary rocks. Gold occurs mainly as the native metal and also as a telluride in the copper-rich zone accompanying pyrite, chalcopyrite, minor bornite, and molybdenite (Boutwell, 1905; Peters and others, 1966). The mined-out part of the porphyry copper body was unusually uniform in composition and could be projected down dip. The subtriangular form in plan is structurally concordant with the major northeast- and northwest-trending faults and the steeply dipping bedding (James, Smith, and Bray, 1961).

The ore zone consists of a network of small fractures a few centimeters apart. Primary copper minerals are dispersed principally along thin fractures, and locally are also disseminated in the highly fractured altered blocks as a replacement of mafic minerals; molybdenite is more commonly found in veinlets. A projection showing the vertical distribution of ore mineral zones (fig. E9) suggests that ore mineral zones thin with depth along the sides of the intrusion. A zone of oxidation and secondary sulfide enrichment from 60 to 250 m thick, composed of chalcocite and covellite replacements of the primary copper sulfide minerals, has been removed by mining. The leached capping contained iron and copper oxides, carbonates, and native copper, in which Boutwell (1905) reported enrichment of gold. Possible formation of any supergene replacement minerals between zones of sulfide enrichment and the leached capping apparently was inhibited by rapid erosion in this area.

During milling, selective flotation is used to recover and separate gold from the silicate and sulfide minerals of the dispersed porphyry copper deposit. Based on published production data, the gold content probably averaged somewhat less than 0.31 g (0.01 oz) of gold per ton of ore; however, current plans to modernize the mine are based on an ore grade of 0.47 g (0.015 oz) Au/ton (Hillman and others, 1984). An oxidized zone, now removed, contained higher values of gold, according to Boutwell (1905); it undoubtedly was the source of placer gold. A part of the copper-rich zone occurs in altered fractured sedimentary rocks bordering the stock, which are mainly removed as waste. The values of copper (and presumably the accompanying gold) in these rocks drop off rapidly in the outer pyrite-rich zone. Some fine-grained gold in quartz may have been lost in the tailings.

Vein and Replacement Gold

Gold and silver occur with copper, lead, and zinc ores in bedding and crosscutting fissures and in manto replacements of limestone beds in the periphery of the Bingham district. These deposits have been described more fully by Hunt (1924), Hunt and Peacock (1950), and Rubright and Hart (1968), and the amount of metals recovered is shown in tables E6 and E7. The bedding fissures occur mainly along the footwall of limestone beds, the result of slippage and brecciation during folding and faulting that accompanied thrusting of the allochthon, and during intrusion of the stocks. Thicker limestone units may contain more than one bedding fissure and locally grade into bedding-replacement deposits. Bedding-fault copper and lead-zinc ore shoots also commonly occur at intersections with northeast-trending cross faults. Copper ore in the western part of the district contained chalcopyrite and pyrite, a sparse quartz gangue, and gold and silver. Scattered, erratically distributed high-grade gold- and silver-bearing ore bodies (shoots) were found at depth in some bedding fissures even though, in general, the amount of precious metals decreased downward as pyrite and silica increased (Rubright and Hart, 1968). Mining as much as 1,370 m down dip on a bedding-fissure body in the Lark mine

Table E8. Average grade by level above and below adit (0) level in a bedding fissure ore body, Lark mine (Rubright and Hart, 1968)

Depths and levels	Au oz/ton
+200 to surface	0.057
0 +200	.012
0	.017
200	.014
500	.015
800	.016
1200	.026
1600	.019
2050	.034
2500	.030
2750	.031
3000	.033
3250	.024

(principal mine locations shown on fig. E3), however, showed a small average increase in grade of gold with depth (table E8).

Mineralized northeast-trending steeply dipping crosscutting veins cut bedding fissures and intrusions, particularly on the south and southwest margins of the Bingham stock. Rubright and Hart (1968) reported that ore was produced from 30 named and many unnamed fault structures across a 3,000 m zone. Some of these fissures have been explored down-dip for more than 1,500 m, and the distribution of ores in these fissures is not appreciably restricted to specific host rocks, as was observed in the upper workings (Hunt, 1924). R.D. Rubright (written commun., 1983) commented that in the U.S. mine more ore came from quartzite- and porphyry-hosted fissures than from limestone-hosted fissures.

The fissure ores consisted mainly of lead or lead-zinc, pyritic copper, and siliceous gold-silver types; the lead and lead-zinc ores carried rare native gold. Rubright and Hart (1968) reported that the gold content of these ores generally increased toward outer fringes and decreased with depth as pyrite increased. Measured from the center of the porphyry, ores at shallow depth in veins were zoned—from 1,200 to 1,500 m, a pyrite and cupriferous pyrite zone; 1,500 to 2,100 m, a lead and lead-zinc zone; 2,100 to 2,750 m, a zone of less lead and zinc with

Table E9. Typical grades of gold in lead-zinc replacement ore shoots in the Lark mine (Rubright and Hart, 1968)

	Average grade (oz Au/ton)	Production amount (oz)
Quartzite[1]	0.038	5,000
Limestone[1]	.019	5,000
Limestone	.090	7,000
Limestone	.022	880

[1]Near intersection with Midas thrust.

increased gold and silver. Gold of extremely varied, sometimes high grade was produced from some of the lead-zinc ore shoots on the lower mine levels. The siliceous gold-silver fissures in the highest levels of the mine contained appreciable copper, lead, and zinc, and graded into lead-zinc deposits. Some of the lead-zinc-bearing fissures of the northeast system were mined for gold close to the outer and upper southwestern limits of ore deposition. Here, calcite and manganese carbonate in gangue minerals occur, particularly where a fissure cuts the unaltered Last Chance stock. Old records show that high-grade copper ore was also mined in association with lead, zinc, gold, and silver. In the Lark mine, on the northeast side of the Bingham porphyry, ores also occurred at the intersections of the Midas thrust fault and crosscutting veins.

Replacement copper and lead-zinc ores occur mainly in the thick (60 m plus) limestone beds between 460 and 610 m from the central part of Bingham stock (Rubright and Hart, 1968). Typical grades of gold for such deposits are shown in table E9. The lead-zinc replacement deposits may occur as far as 1,220 m from this center. Replacement of the whole bed occurred locally, preserving sedimentary rock textures in sulfide minerals. Thinner limestone beds also contained irregular local replacement bodies, particularly where they are cut by cross faults or where they occur within thick zones of highly fractured quartzite. Gold was not persistent throughout the replacement ores, although small local shoots contained from 0.16 to 1.55 g (0.005 to 0.05 oz) Au/ton accompanied by silver and siliceous gangue. Boutwell (1905) reported local high-grade siliceous ore in the oxidized zone of replaced limestones. Small amounts of stibnite, realgar, orpiment, cinnabar, and pyrite formed during a late stage of mineralization that crosscuts sulfide minerals in the U.S. mine, and cinnabar occurred as a coating on galena and sphalerite in fractured quartzites in the Lark mine. Both of these occurrences were about 900 m below the present surface.

The zone of oxidation overlying the vein and replacement deposits generally is shallow. Sulfide minerals occurred at the surface outcrops, but secondary minerals locally formed at depth owing to deep circulation of ground water along some fault systems. Boutwell (1905) reported that black sulfide ores in the zone of oxidation yielded 118.2 g (3.8 oz) Au/ton, 1,822.6 g (58.6 oz) Ag/ton, and 42.3 percent copper, as well as some tellurium.

Skarn Gold

Copper-bearing skarns were formed by contact magnesium- and iron-metasomatism of thick calcareous strata in the Bingham Mine Formation, mainly along the northern and southwestern contacts of the Bingham stock. Hunt (1924) reported that copper ores in the sedimentary rocks close to the porphyry stock were associated with the intensely silicated (skarn zone) limestones. These deposits in the Carr Fork mine were described in more detail by Cameron and Garmoe (1987); earlier studies of the alteration of these rocks are by Atkinson and Einaudi (1978) and Reid (1978). Gold, averaging 1.55 g (0.05 oz) Au/ton, occurs in garnetized limestones that contain ore-grade copper. Higher assays of from 3.1 to 71.5 g (0.1 to 2.3 oz) Au/ton occur locally in silicified and pyritized skarn (Atkinson and Einaudi, 1978). Cameron and Garmoe (1983) observed a close correlation between copper and gold in all skarn ore bodies, and the copper and gold assays increase from hanging wall to footwall in any one ore body; the structurally higher bodies contain higher values of gold. Early pulses of copper mineralization apparently were pervasive and enriched in gold compared to late pulses. BP Minerals America-owned extensions of these skarn deposits underlie an area north of the Utah Copper mine (fig. E3) and have been explored underground.

Placer Gold

The now exhausted gold placers of Bingham Canyon occurred in bench and stream gravels as much as 75 m thick (Boutwell, 1905; Johnson, 1973) and were located mainly in the areas of the Carr Fork, Upper Bingham Canyon, and Bear Gulch branches, downstream to the mouth of the canyon (fig. E3). The source of gold is attributed to the oxidized parts of the nonporphyry ores, where it occurred in the honeycombed siliceous gangue. Some of the fine-grained gold undoubtedly was also derived from the mineralized central porphyry intrusive of the Bingham stock.

Disseminated Gold

An occurrence of disseminated gold in the Barneys Canyon area, about 6 km north of the Utah Copper Mine (fig. E7), is reported to be amenable to open pit mining and bulk-leach gold recovery (Standard Oil Co., 1986). BP Minerals America has plans to mine the deposit. The gold is disseminated in altered carbonate-rich (dolomitic) rocks along the northeast-trending Tooele fault (Tooker and Roberts, 1988). The ore zone contains a number of small workings and prospect pits, relicts of early-day mining. To 1988, an initial reserve of approximately 12.4 metric tons (400,000 oz) of gold has been identified, and additional reserves are expected.

CONCLUSIONS

Over a period of 123 years in excess of 603 metric tons (19.4 million oz) of gold has been produced mostly as a byproduct of base metal mining in the Bingham mining district. The gold has come from placers, metal dispersed in the monzonite intrusions and adjacent sedimentary rocks, veins and replacements, and skarns in the peripheral carbonate strata. Reserves in the district, those measured in the porphyry and skarn deposits, and those inferred in the Barneys Canyon gold prospect, may aggregate more than 505.6 metric tons. The discovery of the disseminated-type deposit at Bingham opens untested potentially favorable ground for exploration and enlargement of the gold reserve in the Bingham district.

The geologic setting for the district is at a favorable structural-stratigraphic-igneous rock juncture. Miogeoclinal carbonate-rich shelf deposits composed of reactive permeable sedimentary rocks were thrust as nappes unknown distances from the west and west-southwest. Asymmetrically folded and locally overturned beds in which the Bingham productive deposits occur were flexed into an arc, and a tensional northeast- and northwest-trending cross fault system formed in response to the maximum stress in the thrust plate. This fractured and potentially reactive zone became the main locus for intrusion of quartz monzonitic stocks similar to those that were intruded along the trace of a cratonal suture zone (Uinta-Cortez axis) in the Wasatch Range, east of Bingham (Tooker, 1971); these latter stocks also are associated with base and precious metal deposits. Closely spaced fissures at Bingham subsequently became conduits into these reactive sedimentary rocks for igneous rocks and hydrothermal solutions, as well as deposition sites for metals carried by the hydrothermal fluids developed in the later stages of the intrusive cycle.

A hydrothermal origin has been proposed for these deposits on the evidence of a brecciated, altered subvolcanic porphyritic quartz monzonite stock that vented boiling mixed magmatic and meteoric waters. Deposition of thermally and mineralogically zoned ores followed. A large volume of finely divided gold seems to have been deposited with copper and iron along fractures and in pores of the central porphyry stock and in adjacent skarns in limestones. The grade of this type of gold is in the range of 0.31–0.62 g (0.01–0.02 oz) Au/ton, locally as much as 1.55 g (0.05 oz) Au/ton in skarns. Equally high grade, but volumetrically less abundant, fine to coarse generally free gold occurs in the uppermost and distal parts of the system that adjoin vein and bedding-replacement deposits in the lead-zinc-sulfide zone. Locally, very late gold occurs in rhodochrosite gangue. Little gold was deposited in the pyritic zone that separates the copper and lead-zinc zones.

These relations suggest the possibility of two (or more) generations of gold—an early high-temperature phase accompanying copper, following brecciation of the porphyry, and one or more later (possibly redistribution) phases in the waning stages of the hydrothermal system. The later phases thus reflect an epithermal low-pressure, low-temperature environment of deposition in open spaces, coating earlier ore minerals. Disseminated gold, discovered along mineralized structures north of the porphyry deposit, ultimately may also be considered part of this late-stage mineral formation.

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APPENDIX—1990 UPDATE

The Bingham Canyon mine was part of BP Minerals America acquired by the RTZ Corp. (London) from BP Petroleum Company in 1989 (Anonymous, 1989a). RTZ will return the Kennecott name to corporate use in the copper mining business in the United States. This acquisition will double the RTZ copper output (Anonymous, 1989b). The Bingham Canyon open-pit mine currently produces more than 200,000 t/yr Cu, 350,000 oz/yr Au, 27 Moz/yr Ag, and 4,000 t/yr Mo. The estimated remaining life of the deposit is 25 years.

The Barneys Canyon deposit contains a gold:silver ratio of 1:1 (Gunter and others, 1990). Anomalous trace elements include arsenic, antimony, mercury, thallium, and barium. Minable oxide reserves are 10 Mt (average 0.046 oz Au/t). The Mel-Co deposit 1 mile southwest of Barneys Canyon mine is spatially associated with a steeply dipping siliciclastic breccia. Minable oxide reserves are 3.1 Mt (average 0.07 oz Au/t). Heap leaching operations began in 1989.

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Gold in the Butte District, Montana

By Edwin W. Tooker

Abstract

The Butte mining district in southwestern Montana was for many years among the top 10 producers of gold, primarily as a byproduct of copper, silver, zinc, and manganese ores. Mining was nearly continuous from 1864 to 1983; open pit mining was resumed in 1986. The placer deposits were exhausted by 1867, and the silver vein lodes became the main productive ores from 1866 to 1888 when the copper lodes were discovered. These sulfide veins and later the dispersed ores have been the main sources of byproduct gold until the present time.

A production figure of 93.311 metric tons (3 million ounces) of gold is undoubtedly under-reported because of poor records during the earliest years. An inferred reserve of 6.594 metric tons (212,000 ounces) of gold may be uncertain owing to the fact that, because of its very low grade, assays of gold in the ores were not obtained.

The district is located in the south-central part of the Boulder batholith, a quartz monzonite (78–73 Ma) intrusive into Proterozoic to Cretaceous sedimentary and volcanic rocks. Aplite and pegmatite dikes and irregular monzonitic masses intrude the batholith. Later quartz porphyry dikes (68–64 Ma) and a plug also intruded the batholithic rocks. Post-ore igneous activity (48–40 Ma) included the emplacement of porphyritic rhyolitic dikes, welded tuff, and volcanogenic sediments. The stages of ore formation in the batholith host rocks comprise (1) pre-Main Stage veins and pervasive alteration in a core zone (64–63 Ma) and (2) the upper Main Stage veins (58–57 Ma) all imposed upon three successive structural-mineralogical domains centered on the core zone. Most of the Butte production has come from underground workings in the Main Stage veins. More recent production has come from lower grade open pit deposits. The ores are distinctively zoned, both vertically and horizontally. The upper Main Stage zone structures persist downward into a dome-shaped domain of pre-Main Stage pervasive biotite alteration and a network of small fractures and disseminated copper sulfides. This zone overlaps a lower dome-shaped molybdenite domain. The fracture system initiated by intrusion of the batholith provided sites for quartz porphyry dikes and vein structures that hosted high-temperature (600 °C) hydrothermal pre-Main Stage solutions. Very little gold has been reported in this high-temperature domain. Much later, lower temperature (300 °C) mixed hydrothermal and meteoric solutions produced the rich Main Stage veins and extensive argillization of the wallrocks. The Main Stage ores were zoned outward from a highly altered central copper- and iron-bearing sulfide zone containing small amounts of gold and silver, an intermediate zone in which copper sulfides predominated and which also contained small amounts of precious metals, and a peripheral zone containing ores of manganese, zinc, lead, and silver, and gold in trace amounts.

INTRODUCTION

Gold has been produced as a primary and byproduct metal from placer, vein, and disseminated deposits in the Butte district in southwestern Montana (fig. E10), almost continuously from 1864 until 1983, when the last mine closed. Open-pit mining was resumed in July 1986. Copper, zinc, manganese, and silver have been the main metals produced; however, until 1980, Butte remained among the top 10 gold-producing districts of the United States. This review of the occurrence and magnitude of the gold in the Butte deposits was obtained from published sources (Meyer and others, 1968; Sales and Meyer, 1950; Klepper, 1973; Miller, 1973; Proffett, 1973; Brimhall, 1977, 1980; Brimhall and others, 1984; Weed, 1903, 1912; Sales, 1913; Perry, 1932; Brown, 1894) and U.S. Bureau of Mines (1973–1982). I am indebted to the late Charles Meyer, longtime participant in the studies of the Butte district as geologist for the Anaconda Minerals Company, for his critical review of this text.

PRODUCTION AND RESERVES

Butte, one of the important mining districts of the world on the basis of its production and known reserves (Miller, 1973), was closed in 1983 because of unfavorable metal prices; however, the district was not exhausted, and contains substantial base and precious metal reserves and resources, which were considered sufficient for reopening under new ownership in 1986. Production began originally in 1864, when shallow placer deposits were discovered. The best placers were worked out by 1867 after about 2.333 metric tons (75,000 troy oz) of

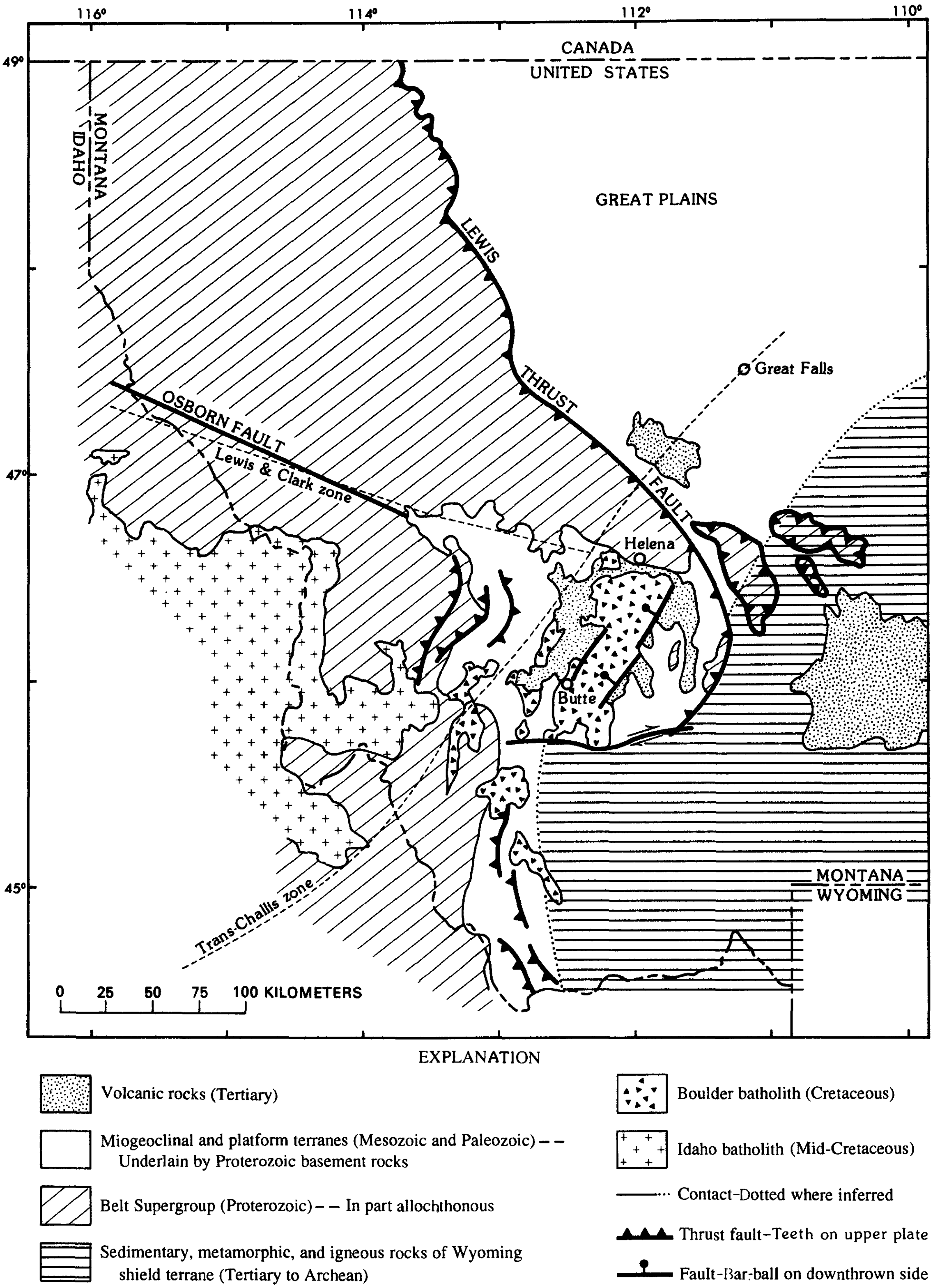

Figure E10. Western Montana, showing location of the Butte mining district and its regional geologic setting, modified from Meyer and others (1968), Smedes and others (1973), and Bennett (1984).

gold were won. Mining of the silver lodes that cropped out nearby on Butte Hill began in 1866. Silver continued as the principal metal sought until the discoveries of poorly exposed copper lodes between 1882 and 1885. From that time until the present, copper has remained the major district product. Other metals, principally zinc,

Table E10. Cumulative gold and associated metal production, Butte mining district, Montana

[Meyer and others (1968); Miller (1973); U.S. Bureau of Mines (1973–1982); oz, troy ounce; t, metric ton; kg, kilogram; n.r., not reported]

Metal	1880-1964	Through 1972	Through 1982
Gold (oz)	2,506,253	2,757,710	2,928,795
(kg)	77,954	85,775	91,097
Copper (t)	7,347,784	8,308,176	9,034,677
Zinc (t)	2,175,344	2,228,287	2,226,272
Manganese (t)	1,680,695	1,680,695	n.r.
Lead (t)	379,774	387,992	387,663
Silver (kg)	[1]20,055,752	[1]621,076,393	702,423,156
Bismuth (kg)	[1]1,833,752	[1]1,833,752	n.r.
Sulfuric acid (t)	[1]8,507,660	[1]8,584,252	n.r.
Selenium (kg)	[1]38,032	143,725	n.r.
Tellurium (kg)	[1]82	107,619	n.r.
Cadmium (kg)	[1]1,848,322	1,953,272	n.r.
Arsenic compound (t)	[1]144,447	n.r.	n.r.

[1]Produced during shorter time, ending in 1964.

manganese, and lead, were actively mined beginning in 1915–1916, but their production declined after the mid-1960's.

Following the early placer period, most of the metal production was from extensive Main Stage vein deposits (Meyer and others, 1968). Production from veins in the underground mines dropped off in the early 1950's, as block caving, open pit mining of the disseminated ores, and leaching of dumps and extraction of metals from acid mine waters became economic for copper production (Miller, 1973, fig. F–1). At one time about 45 companies were active in the district, but through consolidation and purchase this number was reduced to the Anaconda Company, later the Anaconda Minerals Division of Atlantic Richfield. These properties were sold to the Washington Corp., Missoula, Mont., in 1985 (Metals Week, 1985, v. 56, no. 37, p. 8), and mining by the Montana Resources Company began in mid-1986 at the East Berkeley pit, immediately east of the deep (Anaconda) Berkeley pit (Eng. and Mining Journal, 1986). A production figure of nearly 93.33 metric tons (3 million oz) of byproduct gold, shown in table E10, is a compilation of available production data for this district. Early records (pre-1882) undoubtedly are underreported, but the order of magnitude of the district as a producer of gold is clear from these data.

The gold resources at Butte are not well known at present, but they could be substantial if "disseminated" gold were recovered from potential deep copper and copper-molybdenum resources, not currently economic. In the ARCO/Anaconda merger filing (Cox and others, 1981), the published district copper reserves were 154 million metric tons at a grade of 0.67 percent copper (1,031,800 metric tons copper). Assuming that gold will be recovered from this ore in the same ratio as it was from copper production between 1973 and 1982, an inferred reserve of gold in the district could be on the order of 7.558 metric tons (243,000 oz). However, this resource figure may well be too high (Charles Meyer, oral commun., 1984), owing to the fact that no systematic data base exists for recent gold production; gold is irregularly distributed in some parts of the district, and assays for gold were seldom obtained during mining because of gold's relatively low value in terms of total ore value. Thus one cannot be certain that the projected gold:copper ratio will prove accurate for deeper ores.

GEOLOGIC FEATURES

Regional Setting

The Butte district is located in the south-central part of the Boulder batholith, which is intrusive into the cratonal platform of North America. The batholith lies close to the boundary between the platform and Wyoming shield terranes (King, 1976) on the south, and at the junction of at least two major craton platform lineaments, the west-northwest-trending Lewis and Clark (Meyer and others, 1968) and the northeast-trending trans-Challis–Great Falls (Bennett, 1984) zones, on the north and west. The trans-Challis lineament separates the Boulder batholith from the Idaho batholith to the west (fig. E10). The shield is composed of Archean gneiss, schist, and granite, and has remained a stable undeformed structural entity since its formation in the Precambrian. The Boulder batholith intruded and metamorphosed Proterozoic to Cretaceous sedimentary cratonal, miogeoclinal shelf, and volcanic rocks. Where exposed, volcanics form the roof of the batholith (Smedes and others, 1973). To the north and west, folded Proterozoic Belt Supergroup clastic rocks have been thrust northeastward over Paleozoic and Mesozoic formations on the Lewis thrust fault.

The Boulder batholith was forcefully emplaced, in stages (Klepper, 1973), into an unstable deformed zone between the cratonic basement structures, during the Laramide orogeny of Late Cretaceous age (80–70 Ma). Smedes and others (1973) estimated that the intrusion lifted up the eastern part of the batholith roof between 900 and 3,000 m along a border fault. A roughly concordant western margin dips gently westward under roof rocks. The north and south margins of the batholith lie along complex cross fault zones. Of the individual plutons in the batholith, the Butte Quartz Monzonite is the largest, and was one of the later intrusive phases formed. The most important lead, zinc, and silver deposits in this region are located within or along the contacts of the Butte Quartz Monzonite. Meyer and others (1968) proposed that Butte deposits probably were derived from a different unexposed(?) later intrusion that activated the large complex copper-rich base- and precious-metal sulfide system.

District Setting

Details of the geologic features of the Butte district (fig. E11) and their interpretation are well documented by Weed (1912), Sales (1913), Meyer and others (1968), Proffett (1973), Brimhall (1977), Roberts (1973), and Gustafson (1973). The significant points in the evolution of host rocks, ore-bearing structures, and hydrothermal events are summarized in table E11.

Host Rocks

Three groups of igneous intrusives form the district host rocks at Butte (Meyer and others, 1968). The oldest, the Butte Quartz Monzonite, is medium to coarse grained, and is composed of 40–45 percent quartz and orthoclase (microperthite) in equal proportions, 36–40 percent plagioclase, and 15–20 percent hornblende and biotite. The second group of intrusives includes aplite and pegmatite dikes and irregular monzonite masses composed mainly of quartz and potassium feldspar, and locally including tourmaline and sulfide minerals. These latter intrusives are scattered throughout the quartz monzonite. The youngest group, three nearly vertical quartz porphyry dikes 3–15 m thick, intrude the quartz monzonite, trending west to west-northwest across the district. The quartz porphyry of the dikes is composed of quartz, feldspar, and sparse biotite phenocrysts in a fine-grained groundmass of quartz and alkali feldspar (Proffett, 1973). The porphyry is brecciated locally and cut by quartz and quartz-molybdenite (pre-Main Stage?) veinlets.

An irregular quartz porphyry plug (the Modoc) of similar petrographic characteristics is present in the northeast part of the district. Breccias associated with this mass include quartz porphyry and Butte Quartz Monzonite fragments, which contain quartz-molybdenite veinlets with potassium-silicate alteration envelopes. The matrix of these breccias is "sand" cemented by potassium feldspar and biotite. The Modoc plug may have been emplaced later than the set of southern quartz porphyry dikes during the potassium silicate phase of alteration (pre-Main Stage). But like the southern dike set, it is everywhere cut by Main Stage veins.

Table E11. General sequence of igneous, hydrothermal, and structural events in Butte mining district

[From Meyer and others (1968), Miller (1973), and Proffett (1973)]

Relative age (Ma)	Events
Pleistocene(?) & Pliocene(?)	Continental fault, Basin-Range structure; zone 30-90 m wide, north-trending, steeply west dipping; 900-m downward displacement on west; no hypogene minerals.
	Rarus and Middle normal fault systems, northeast- and east-trending, moderately northwest dipping, 10-100 m downward displacements in south; cut main stage faults; no hypogene minerals.
	Regional post-ore tilting, $\geq$25° NW.
48-40	Rhyolite (porphyritic quartz latite or rhyodacite), east-trending dikes and Big Butte intrusive complex, west of district.
58-57	Main Stage vein systems, complexly intersecting; reverse S-curvature structural grain; altered wallrocks:
	Hanging Wall Steward--strikes east, dips gently south; banded quartz-molybdenite veins at depth are cut by Main Stage sulfides; good ore at depth, spotty above; offsets the Steward vein system.
	Steward--trends east-northeast, dips steeply southeast; normal displacement of 45 m; wall rocks intensely altered; a few ore shoots in upper parts; much post-ore displacement.
	Blue--trends northwest, dips southwest; left lateral displacement of a few hundred feet; offsets Anaconda system; fault gouge; some post-ore movement; prominent ore shoots.
	Anaconda--trends northeast to east-northeast with en-echelon gaps; dips steeply both to north and south; small right-lateral displacements of <30 m; horsetail structures on east end; wide (10-30 m) mineralized zones; major ore producer.
63-60	Pre-Main Stage, potassium-feldspar alteration of quartz monzonite at depth; formation of small vein systems and injection of banded quartz-pyrite-molybdenite veinlets in core zone.
68-64	Quartz porphyry dike emplacement.
70	Crosscutting aplite, pegmatite, and granoaplite dikes, mainly on periphery of mineralized-replacement zone.
78-73	Butte Quartz Monzonite intrusion.

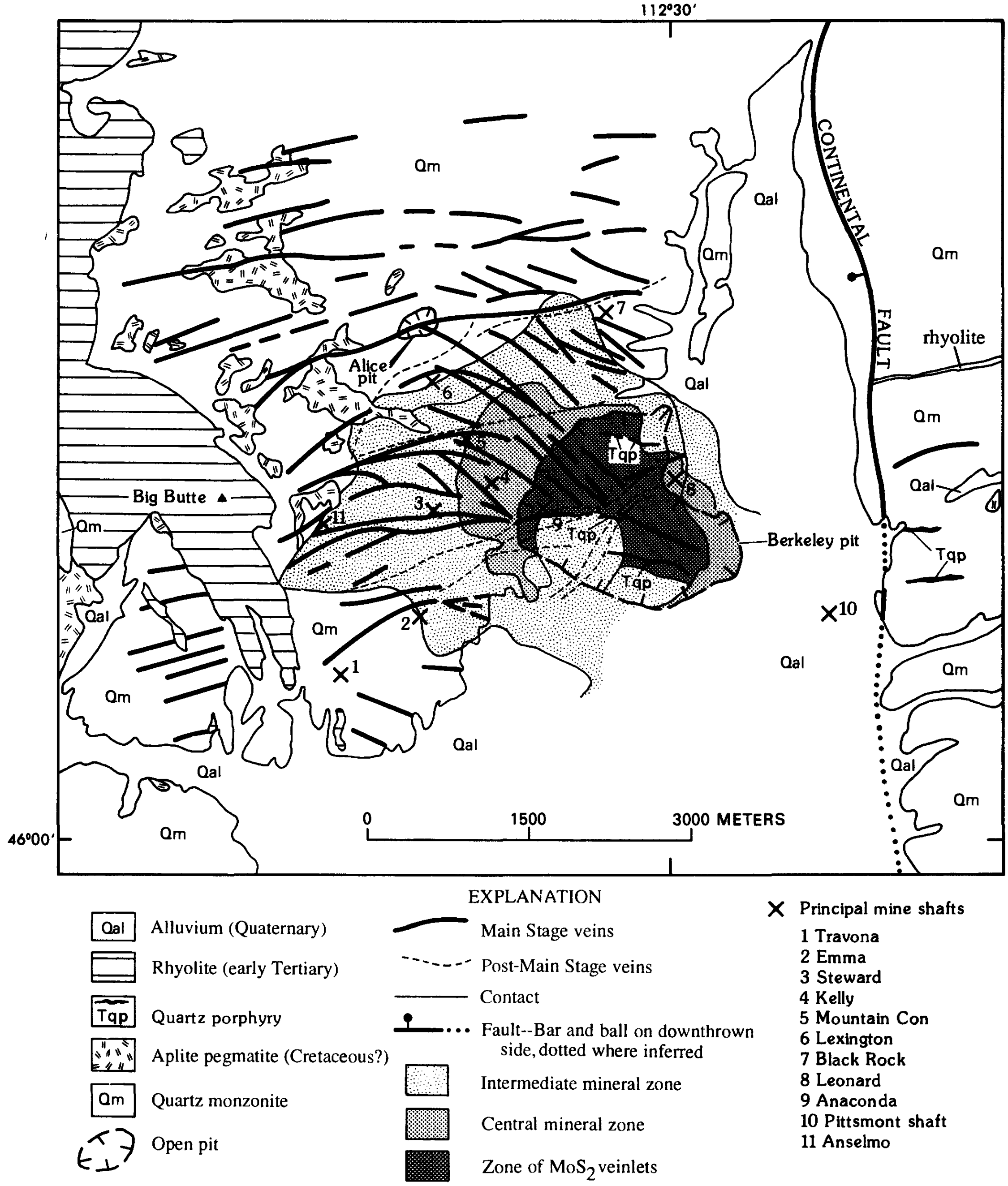

Figure E11. Generalized map showing location of main underground mine shafts and open pits, the principal geologic lithologies, and vein structures of the Butte mining district (modified from Miller, 1973). Map area covers the northwestern part of the city of Butte.

Post-ore igneous activity is recorded by the intrusion of porphyritic quartz latite or rhyodacite (locally called rhyolite) dikes and the emplacement of welded tuff and volcanogenic sediments.

Structures

Meyer and others (1968) inferred that stresses accompanying the intrusion of pre-mineralization host rocks at Butte also initiated a regional fracture system in the quartz monzonite that provided pathways for magma and fluid migrations in the district. Emplacement of the magmas and associated fluids resulted in the formation of distinctive structural-mineralogical domains.

Nearly all the Butte production of base and precious metals has come from the uppermost of three structural domains (fig. E12) characterized by large Main Stage veins and by intersecting zones of closely spaced fractures whose walls are extensively altered sequentially into argillic and sericitic zones (described in detail by Sales and Meyer, 1950). These vein structures contain relatively low temperature (300 °C), zoned base-metal sulfide ore assemblages (Meyer and others, 1968). Two principal Main Stage vein systems include the Anaconda, a steep east-northeast- to east-trending system, and the Blue, a northwest-trending system. Sales (1913) recognized a third, less well developed system, the steep northeast-trending Steward system; and Meyer and others (1968) described a fourth east-trending gently south dipping system found in deep workings, the Hanging Wall Steward system. These interrelated systems form a reverse S-curvature, locally producing the well-known horsetail structures of the Butte district. Gustafson (1973, fig. J–1) showed that these structures occur where the eastern ends of the Anaconda east-trending veins are dissipated along their south sides into a network of small southeast-trending ore-bearing veinlets and disseminations, surrounded by highly altered wall rocks. The width of the network of these veinlets and disseminations varies along strike and with depth. The Anaconda system has en-echelon gaps where veins thin or disappear, but it has been mineralized over long horizontal and vertical distances (Meyer and others, 1968). The average width of ore shoots is 6–9 m, but locally, where the strike changes, some are as wide as 30 m. The horsetail ore bodies are as much as 18 m wide and have been mined to depths greater than 600 m. The Blue vein ore shoots are not as wide (1.5–6 m) or as persistent laterally (30–730 m) or vertically (180–550 m). The Blue system commonly is lower in grade at the surface, but a more important ore producer in lower levels. Most veins have been displaced along strike, and possibly some tensional opening of veins has occurred. Meyer and others (1968) believed that the fracture pattern occupied by the Main Stage was incipient in quartz monzonite before the large Main Stage veins were fully opened and filled. Proffett (1973) confirmed that in the deeper levels most if not all the important Main Stage veins fill fractures that earlier were quartz-molybdenite veins. Meyer and others (1968) suggested that some of these early veins preceded Main Stage veins by at least 5 m.y.

Many of the Main Stage fractures continue downward into a second, lower structural domain, which was described by Roberts (1973) as a single large outward-dipping, elongate dome-shaped form (fig. E13), roughly concentric with the Main Stage ore zonal pattern, and which trends southeastward from beneath the Berkeley pit to east of the Continental fault zone. This domain is characterized by pervasive pre-Main Stage biotitization of hornblende in the quartz monzonite along a network of small fractures, and the dissemination of chalcopyrite, pyrite, and bornite, generally in sites of the former mafic minerals in the walls of fractures. The original plagioclase, quartz, and accessory minerals are unaltered. The biotite alteration-structural domain may represent a zone of overlap between a molybdenite dome below, and Main Stage vein zone above.

The third (also pre-Main Stage) domain (fig. E13), which underlies the pervasive biotitic alteration domain, beginning at about 850 m level below the surface, is called the molybdenite dome or domain. This domain is characterized by an early high-temperature fracture-controlled quartz-molybdenite vein and a disseminated pyrite and chalcopyrite assemblage in the Butte Quartz Monzonite. Where the quartz-molybdenite veins split off from the Main Stage system, part of which persists to this depth, the wallrocks generally show thin rinds of potassic alteration. The molybdenite domain is exposed at the surface east of the Continental fault, which is believed to have an offset (down on the west) of nearly 1,600 m. The base of the molybdenite domain has not yet been observed.

Following the Main Stage, intrusive rhyolite crosscut the district as a broad dike, and formed a flow-banded complex intrusive in the Big Butte area on the west side of the district (Proffett, 1973). Rhyolite, welded tuff, and volcanogenic sediments on the west side of the district record a subsequent regional tilting of 25° to 50° to the northwest in some fault blocks.

Later, the generally unmineralized normal faults, the Rarus and Middle, were formed, trending northeasterly to easterly across the district. A final structural event was north-trending Basin-Range faulting along the Continental fault zone on the east side of the district.

Evolving Environment of Ore Deposition

Ore formation, as deduced by Meyer and others (1968), resulted from a long-term, perhaps continuous series of events, summarized in table E12. Intrusion of the Butte Quartz Monzonite pluton initiated a fracture system along which subsequent quartz porphyry and perhaps an as yet unidentified(?) deep earlier porphyritic intrusion were emplaced. These porphyritic intrusions generated a high-temperature (600 °C) hydrothermal event and deposited a pre-Main Stage quartz-molybdenite assemblage in veinlets, and disseminated pyrite and chalcopyrite within potassium-silicate-altered vein walls of the molybdenite dome domain. This hydrothermal event may have created the overlying pervasive biotitic alteration domain containing pyrite and copper sulfide veinlets (Roberts, 1973). Brimhall (1980) considered these porphyry copper-type assemblages as the

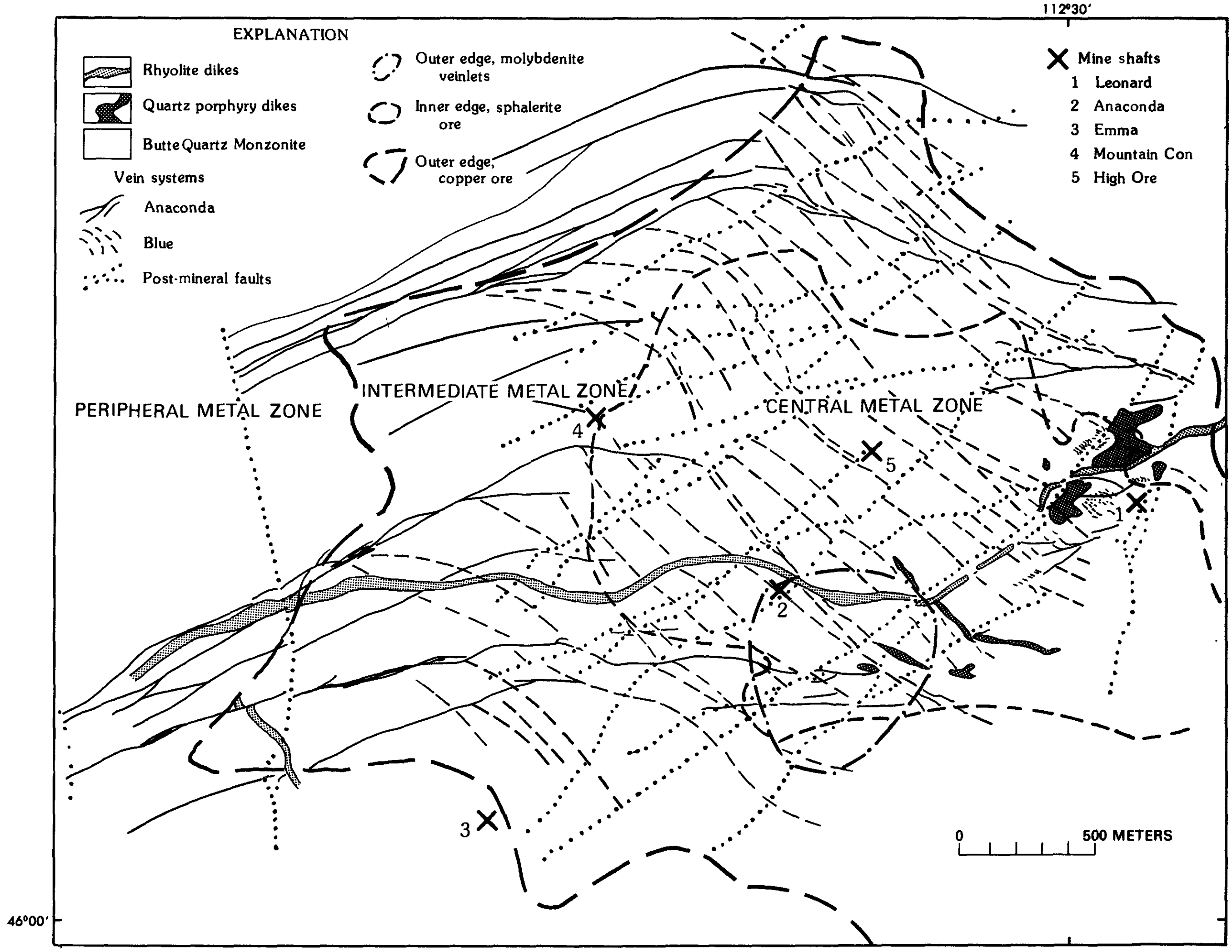

Figure E12. Generalized plan of the 2800 level of the Butte district showing the main vein, fault, and dike systems in Butte Quartz Monzonite and the Main Stage mineral zones that surround the central pre-Main Stage zone containing molybdenite veinlets (modified from Meyer and others, 1968).

protore for the Main Stage; however, a deeper source for some of the base metal sulfides may be required because of the huge volumes of base metals, sulfur, and arsenic in the Main Stage veins and scant evidence for depletion of copper sulfides in the molybdenite dome.

Perhaps 5 m.y. later, possibly during an unrelated magmatic intrusion interval during which deep crustal faulting was developed (according to Meyer and others, 1968), a lower temperature (300 °C) hydrothermal Main Stage system evolved, which allowed meteoric water to penetrate to deep levels. These solutions mixed with magmatic fluids and picked up metals from a deep source, then moved up through the pre-Main Stage zone, where additional metals were added through hypogene leaching. Thus, through a process of hypogene alteration, oxidation, leaching, and redistribution, the base and precious metals were flushed upward into the extensive open near-surface fissures. Base and precious metal veins (mainly composed of chalcocite-enargite-bornite-chalcopyrite-pyrite) were formed in the central and intermediate metal zones, and zinc, lead, manganese, and silver-gold veins developed in the intermediate and peripheral metal zones. The vein openings were wider in the central ore zone than in the outer ore zones, which latter presumably were cooler and farther from the source. The solutions produced extensive argillic alteration of the central zone vein wallrocks; the amount of alteration decreased in peripheral zones. The Main Stage veins everywhere cut quartz-molybdenite veinlets but also were emplaced along strike of some large quartz-molybdenite veins. Sulfur isotopes indicate a genetic relation of magmatic-hydrothermal solutions to Butte Quartz Monzonite, and that the sulfur probably was of crustal rather than subcrustal origin (Lange and Cheney, 1971). Sulfur isotopes of early pre-Main Stage solution were different from those of the Main Stage.

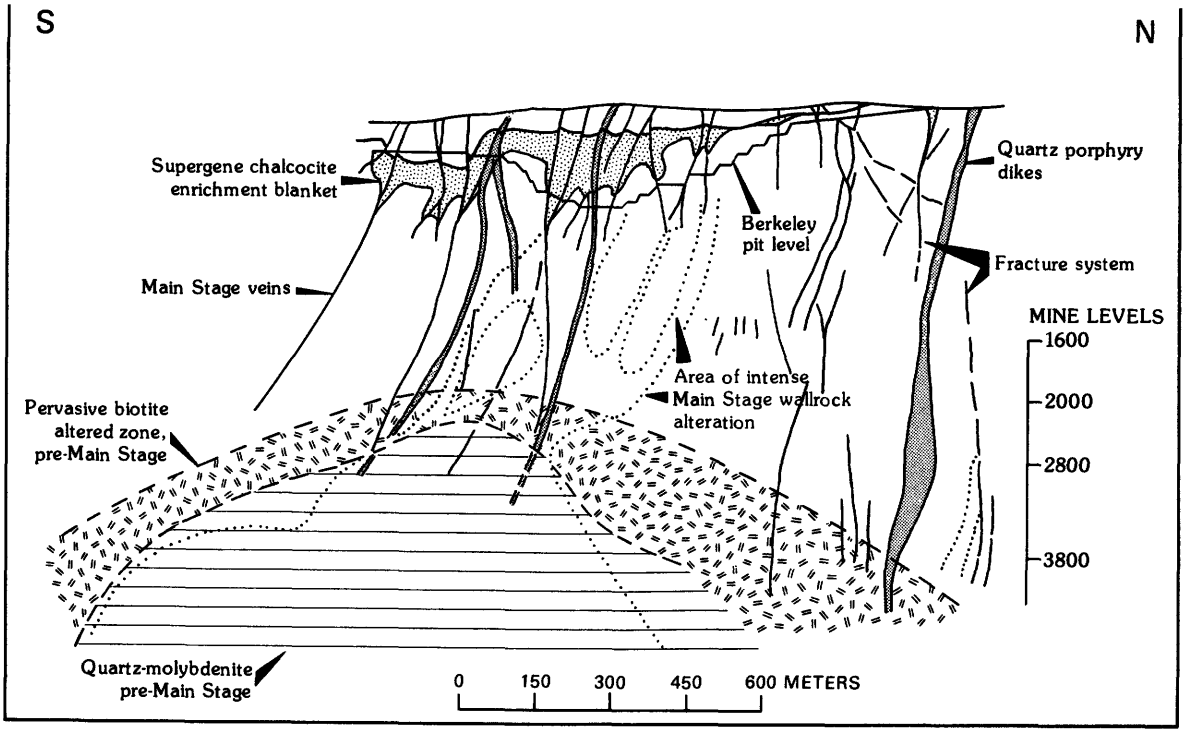

Figure E13. Generalized north-south cross section through the Butte district, vicinity of the Berkeley pit, showing location of molybdenum dome, domain of pervasive biotitic alteration, the Main Stage vein zone, supergene chalcocite enrichment blanket, and zone of surface oxidation. A zone of intense hypogene wallrock alteration generally parallels the vein fractures and porphyry dikes. Modified from Brimhall and Ghiuso (1983).

Table E12. Summary of geologic attributes of ore zone domains in Butte mining district

[From Meyer and others (1968), Proffett (1973), Roberts (1973), and Miller (1973)]

Ore type	Vein type	Vein minerals	Wallrock alteration	Alteration assemblage
Main Stage base and precious metals.	Wide veins; sericite K-Ar age 57.3-58 Ma.	District-wide hypogene zonation; central copper; intermediate copper-zinc-silver; peripheral zinc-lead-manganese-silver(?) (oxide, sulfide, carbonate,and silicate; sulfate gangue); temp. 200-350 °C.	Varied, depending on position in ore zone; broad where veins are wide or closely spaced (horsetail zone) in central ore zone; narrower in peripheral ore zone.	Sequence outward from vein: sericite, white argillic, green argillic, and fresh quartz monzonite (see Meyer and others, 1968, fig. 14).
Pre-Main Stage copper sulfides.	Network of small veinlets in elongate domal structure (overlaps lowest domain, concentric with Main Stage zones).	Quartz, molybdenite, chalcopyrite, pyrite; temp. 550-700 °C.	Pervasive biotitic alteration "dome": plagioclase, biotite, potassium feldspar, quartz, and accessories; not altered.	Original hornblende altered to biotite, quartz, and anhydrite; chalcopyrite, pyrite, and bornite disseminated in wallrock.
Pre-Main Stage molybdenite dome.	Narrow, discontinuous veinlets, varied orientations.	Fine-grained quartz, alkali feldspar, biotite, opaque minerals (molybdenite, chalcopyrite, pyrite, magnetite); temp. 600-690 °C.	Host rocks everywhere altered, but only in narrow zone along vein.	Secondary alkali feldspar, quartz, sericite, biotite, and opaque minerals; grades outward to fresh host rocks.

The Main Stage oxygen isotope composition is believed to be indicative of hydrothermal solutions containing a large component of meteoric origin (Sheppard and others, 1969).

More recent supergene enrichment of the veins at the surface has produced a chalcocite blanket.

Zonal Distribution of Main Stage Base and Precious Metals

As observed by Sales (1913), early in the development of the upper parts of mines in the district, three nearly concentric zones of Main Stage metals or ore minerals occur in the veins (fig. E12): (1) a highly altered central zone containing mainly copper and iron-bearing sulfide minerals in which small amounts of gold and silver also occur; (2) an intermediate zone in which copper sulfide predominates but which also contains some zinc sulfide ores as well as small amounts of gold and silver; and (3) a peripheral zone containing ores of manganese, zinc, lead, silver, and traces of gold. The metal zones broaden with depth and were capped by successive oxidized, leached, and enriched supergene blanket deposits. These post-Main Stage supergene deposits in the zone of oxidation contained quartz, as well as copper, manganese, iron, and silver oxides, but no gold. A fourth metal zone encountered in deeper workings beneath the central metal zone contains the pre-Main Stage quartz-pyrite-molybdenite-chalcopyrite assemblage (of the molybdenite dome), and little reported gold (Meyer and others, 1968).

PRECIOUS METALS IN BUTTE ORES

Gold is a minor but not insignificant constituent of Butte base metal–silver ores. The occurrence of gold is believed related to that of the copper sulfides; however, gold at Butte is so finely dispersed that its association with any specific sulfide mineral has been difficult to determine.

Widely varied gold values reported in the early literature suggest an irregular distribution of gold in the near-surface early-mined Main Stage deposits. Brown (1894) reported gold values of 62.2 g (2 oz) Au to 3,110 g (100 oz) Ag associated with fine-grained pyrite and to a lesser extent with galena and sphalerite. By 1897, about 15.5 metric tons (0.5 million oz) of gold had been produced, and Emmons and Tower (1897) commented on the waning of placering sources. Abandonment of placer mining occurred in part because of large amounts of silver alloy in placer gold, which resulted in low bullion values. Emmons and Tower (1897) also reported that the grade (5 month average) in vein ore was about 1.86 g Au/metric ton (0.055 oz Au/ton), with local richer concentrations in the silver-rich ores. Weed (1912) observed that each pound of copper contained 1.16 g (0.0375 oz) of silver and $0.0025 (about 0.004 g or 0.00012 oz) of gold. By 1910, 34.2 metric tons (1.1 million oz) of gold had been produced. Weed reported that the copper ores contained little silver, that the silver ores rarely contained copper, but that copper and silver ores both contained gold. High-grade silver ores contained highest gold values; however, the average gold values for all mines during that period was 0.093 g Au/metric ton (0.003 oz Au/ton). In the Leonard mine some spotty high-grade (as much as 1.06 g Au/metric ton (0.03 oz Au/ton)) occurrences of gold were associated with the presence of tetrahedrite, a rare mineral at Butte. Free gold was rare but did occur in some silver ores, and was observed on some galena surfaces. Weed noted the common association of gold, tellurium, and selenium in smelter returns. Sales (1913) reported that by 1912, 38.6 metric tons (1.24 million oz) of gold had been produced from 65 million tons at a grade of 0.017 oz Au/ton. Analyses of samples from oxidized parts of productive copper veins reported variations in gold content from 0.16 to 2.2 g Au/metric ton (0.005 to 0.064 oz Au/ton). Higher values occurred in silver veins, generally associated with tetrahedrite. The location of these ores was not specified, but it is presumed that the ores represent the district at large. Perry (1932) reported cumulative gold production through 1931 as 57.2 metric tons (1.84 million oz). Native gold occurred commonly, usually as wires, generally associated with chalcocite. Gold occurred in ore shoots as rich as $100 (about 155.5 g Au/metric ton or 4.5 oz Au/ton); all ores contained gold and silver, but copper ores contained 10 times as much gold and one-third as much silver as zinc ores. Average copper ore (4–5 percent Cu) contained 0.31 g Au/metric ton (0.01 oz Au/ton) and 62.2 g Ag/metric ton (2 oz Ag/ton). Average zinc-lead ores contained 0.25 g Au/metric ton (0.007 oz Au/ton) and 264.4 g Ag/metric ton (8.2 oz Ag/ton); manganese ores contained negligible gold.

Very little information about the occurrence and abundance of gold in deeper workings at Butte was published subsequently until Meyer and others (1968) indicated that gold is rare at depth in the central, intermediate, and peripheral zones. The best grades occurred in local ore shoot concentrations in the intermediate and peripheral zones of the Main Stage. Gold is much less abundant in the pre- and post-Main Stage ores. Traces of gold occur in the pyrite-poor supergene zone, but not in pyrite-rich parts. Brimhall and others (1984) recently have considered the zoning of precious metals within base metal sulfides in the central zone. They found that the pattern of distribution of gold and silver in the sulfides was similar, and they postulated that the pattern was controlled by steep faults related to late-stage porphyry intrusives, with which was associated the formation of the Main Stage veins, as well as acid-sulfate alteration. In a zone between two steeply dipping faults, the precious metals were concentrated locally to depths of 1,220 m below the supergene chalcocite blanket in a chalcocite-digenite-pyrite Main Stage assemblage. Precious metals outside this zone occur in a bornite-chalcopyrite-pyrite assemblage. The Ag:Au ratio decreases generally upward. Brimhall (1979) and Brimhall and others (1984) believed that gold was introduced late in the formation of Main Stage veins, long after formation of the pre-Main Stage copper protore, which has a very low gold and silver content.

CONCLUSIONS

Resumption of copper production at Butte will result in the production of additional byproduct gold. The amount of gold remaining in unmined copper ore reserves is difficult to assess because of the lack of systematic assays for gold in mined ores. As a minor constituent of ore, the gold was not worth the cost of analyses even though it was recovered (Charles Meyer, oral commun., 1984); and although a great deal of published geologic, geochemical, and mineralogic data is available, information on the occurrence of the gold in these deposits is fragmentary. First, the district production of nearly 93.3 metric tons (3 million oz) itself is an approximation, owing to under-reporting in the earliest days, and lumping of Butte production with other production data from more recent times. Virtually no data have appeared on the mineralogic occurrences and grade of gold mined since 1930; some data indicated the grade of early-mined ores as on the order of 0.09–0.93 g Au/metric ton (0.003–0.03 oz Au/ton). As a consequence of gold's being a minor byproduct, no hard information exists about the regularity of distribution of trace amounts of gold in recently mined ores. Meyer and others (1968) reported that gold is associated with base metal sulfides in all Main Stage ore zones; the best grades are in local intermediate and peripheral high-grade shoots. Little was reported in pre-Main Stage mineralized material, and trace gold was found in the supergene enrichment blanket. More recently Brimhall and others (1984) have used mineral analysis and mathematical analytical methods to determine that beneath the Berkeley pit in the central copper ore zone, gold occurs in several iron and copper sulfides, is structurally controlled by deep-reaching veins, and that the Ag:Au ratio generally decreases upward in this part of the system, which they consider evidence for strong metal zonation upwards.

From these several observations, the status of inferred gold reserves, which is based on the copper reserve at Butte, must be considered uncertain. The indication that gold content in sulfide ores decreases downward suggests that an estimated inferred reserve of 7.558 metric tons (243,000 oz) may be overly optimistic. Nevertheless, a substantial resource of gold is indicated; only the amount is inferred.

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APPENDIX—1990 UPDATE

In 1989, Asarco purchased a 49.9 percent interest in a new partnership formed by Montana Resources, Inc., to own the latter's Montana copper mining business, which includes the former Anaconda properties at Butte, Mont. Montana Resources operates the Continental open pit mine at Butte, which in 1988 produced 53,200 tons of copper and 14.1 million pounds of molybdenum in concentrates. The mine has ore reserves of 468 million tons averaging 0.31 percent copper and 0.043 percent molybdenum (Anonymous, 1989).

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Gold in the Ely (Robinson) Copper District, White Pine County, Nevada

By Laurence P. James[1]

Abstract

The Ely or Robinson copper district has yielded about 3 million troy ounces of byproduct gold, recovered during milling and smelting of porphyry copper ores. Compared to many porphyry copper systems, a relatively high trace-gold content is present. Gold appears preferentially concentrated in the upper and outer zones of the porphyry system. Small ore bodies of considerably higher grade (more than 0.1 ounce gold per ton where oxidized) have been delineated in these peripheral zones. The smaller ore bodies exhibit varied degrees of structural and stratigraphic control, and highly varied primary sulfide content. Typically they are low in copper and silver, and only moderately anomalous in arsenic. A disseminated body currently being mined is localized in silicified calcareous sandstone, adjacent to the principal copper ore trend. Gold ores more distant from the porphyry system are mainly structurally controlled and typically have a higher tellurium content than the disseminated body.

The district preserves features from zones greatly different in depth of formation, subsequently dissected and juxtaposed by low-angle faulting. Mineralization and accompanying alteration took place during the cooling of some phases of a Cretaceous intrusive quartz monzonite system, emplaced into a west-trending, probably south dipping regional structure. Virtually all known peripheral gold mineralization was localized in the hanging wall of this structural zone, in sedimentary rocks of Mississippian to Permian age. Controls of gold mineralization included proximity to the porphyry system, structures such as faults and fractures, and permeable siliceous-calcareous stratigraphic units. Mineralogy of gold-rich copper ores of the district differs from many porphyry systems in that bornite and enargite zones are lacking. High-grade gold zones are unknown in the igneous rocks of the district.

A mid-Tertiary sequence of volcanic rocks, including diatremes, tuffs, pyroclastic units, and a garnetiferous rhyolite dome locally cut and conceal copper- and gold-bearing deposits. The volcanic rocks bear no relation to genesis of primary ores.

INTRODUCTION

The Ely or Robinson mining district lies in White Pine County, in the Basin and Range province, east-central Nevada (fig. E14). The porphyry copper deposits that brought prosperity to the district and the region occur in an 11-km-long west-trending belt extending from near the town of Ely to west of the mining town of New Ruth. The belt crosses a low summit in the north-trending Egan Range, immediately south of U.S. Highway 50 (fig. E15).

In 1867, prospectors discovered siliceous, iron-rich gossans in Lane Valley, between the present towns of Ely and New Ruth (fig. E15). These were first mined for precious metals, as were nearby irregular veins (Raymond, 1872, p. 158). Early records (rather incomplete) show ore was mined, milled, and smelted as early as 1873–1877 at the Aultman and Saxton mines near the Chainman mine (fig. E16) and at other small mines (Spencer, 1917, p. 93; Read, 1965, p. 267) in Lane Valley. The Chainman mine, until recently the most productive precious-metals mine in the district, was extensively developed by the 1890's. One or more small cyanide plants operated intermittently near Lane City until the 20th century, producing bullion from these and other small mines. Lessees reopened some of the mines in the 1930's and 1970's during periods when the nearby copper smelter purchased siliceous flux.

The Giroux Consolidated Mining Company was organized in 1903 and the Nevada Consolidated Copper Company in 1904 to mine copper. Nevada Consolidated started construction of a mill and smelter at McGill, 27 km northeast of Ely, in 1906, and the first copper from the district was produced in 1908. Consolidated Copper Mines Company took over operations from Giroux and several other mining companies in 1913. Both Nevada Consolidated and Consolidated Copper Mines closed

[1]BHP-Utah Minerals International, Kagoshima-Shi, Kyushu, Japan.

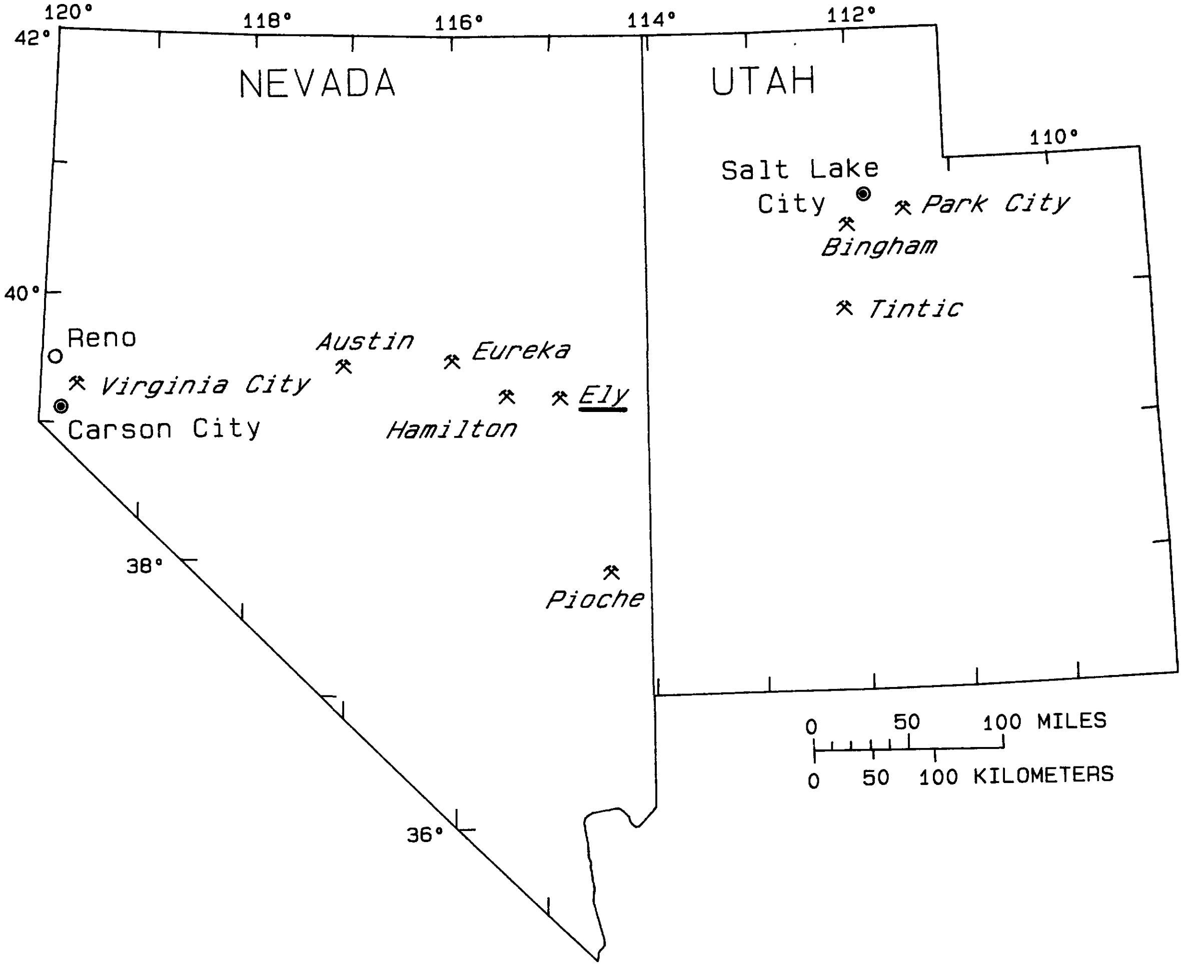


Figure E14. Map showing location of the Ely (Robinson) mining district, Nevada.

down briefly following World War I. Consolidated Coppermines Corporation was reorganized in 1922; Kennecott Copper Corporation took over Nevada Consolidated in 1933, and became the Nevada Mines Division of Kennecott in 1943. In 1958 virtually all properties in the Ely district were consolidated into a single holding by the Nevada Mines Division of Kennecott. (Data are from Lincoln, 1923, and Smith, 1976.)

Descriptions of the early silver-gold mines were presented by Spencer (1917), and by mining journals. These reports, a few unpublished reports from the 1930's, and two reports on the distribution of gold, silver, tellurium, and mercury (Gott and McCarthy, 1966; McCarthy and Gott, 1978) are the only literature on these deposits. Spencer (1917, p. 98) estimated a total production of $600,000 in gold plus silver prior to 1902. As no large silver producers were noted in the district, it seems reasonable that only about 22,000 oz of gold was produced, if 75 percent of $600,000 in actual production is assumed to have been gold at $20.67/oz. The Chainman mine was reworked as a small open pit in the late 1970's, producing gold-bearing high-silica smelter flux. Production figures for this period are not available.

To the mid-1980's the largest share of the district's gold production has been a byproduct of copper mining and smelting. The relatively low grade copper ore in porphyry and in altered limestone was mined by both underground and open-pit methods. Most of the ore was concentrated and smelted at McGill. Gold was recovered from canvas-lined launders in the copper sulfide flotation plant (mainly in the 1930's) and during electrolytic refining of the blister copper, conducted outside Nevada. Because of the steady production of copper, the district was also the leading gold producer in Nevada in years when gold mines were not producing heavily; as of 1960, it was third in total gold production in the State, having produced an estimated 1,959,659 oz between 1902 and 1959 (Koschmann and Bergendahl, 1968). Copper mining produced about 339 million tons of ore, mainly sulfide, between 1908 and 1977 (Wilson, 1978); operations ceased in 1978. Latest cumulative gold

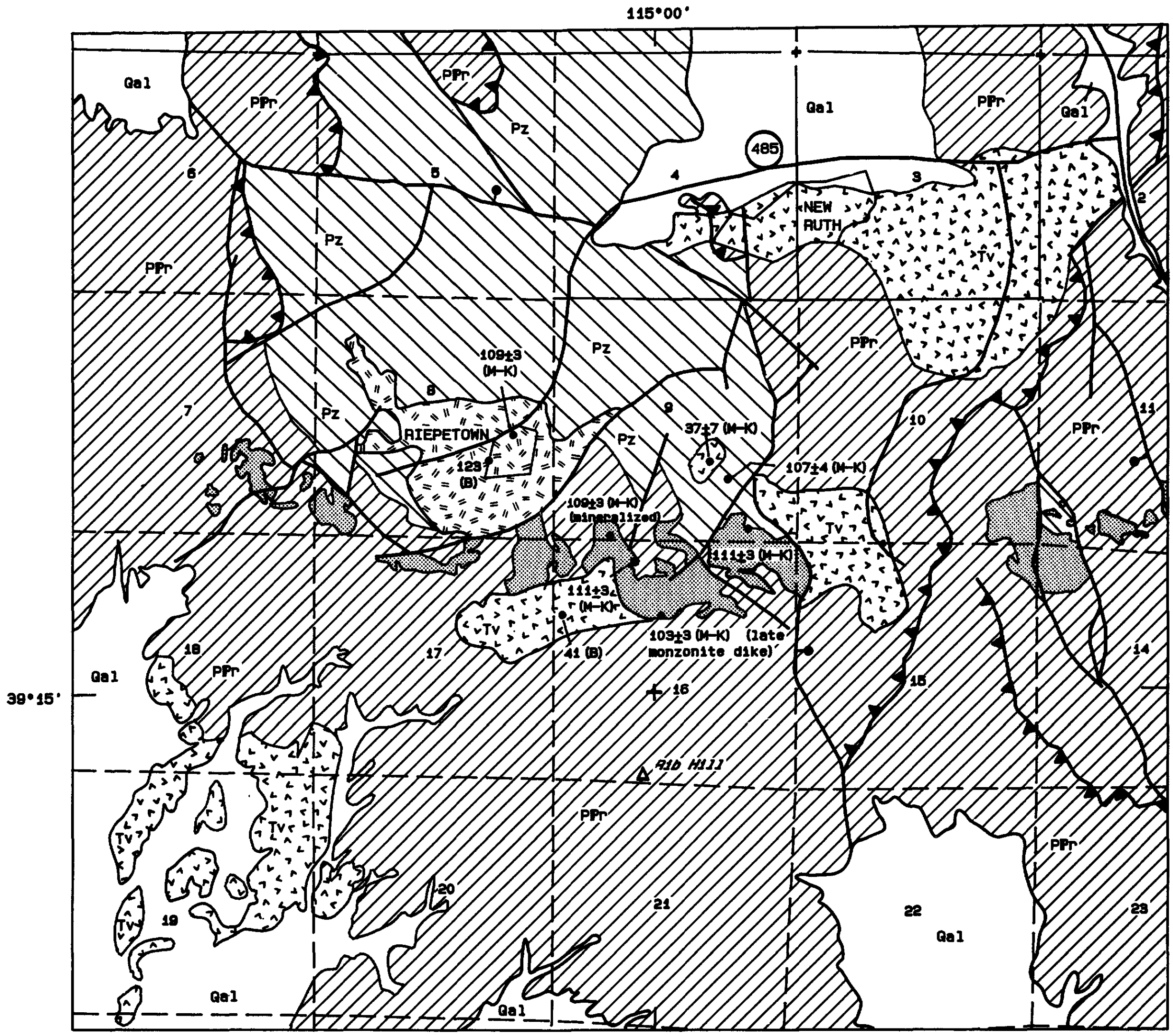


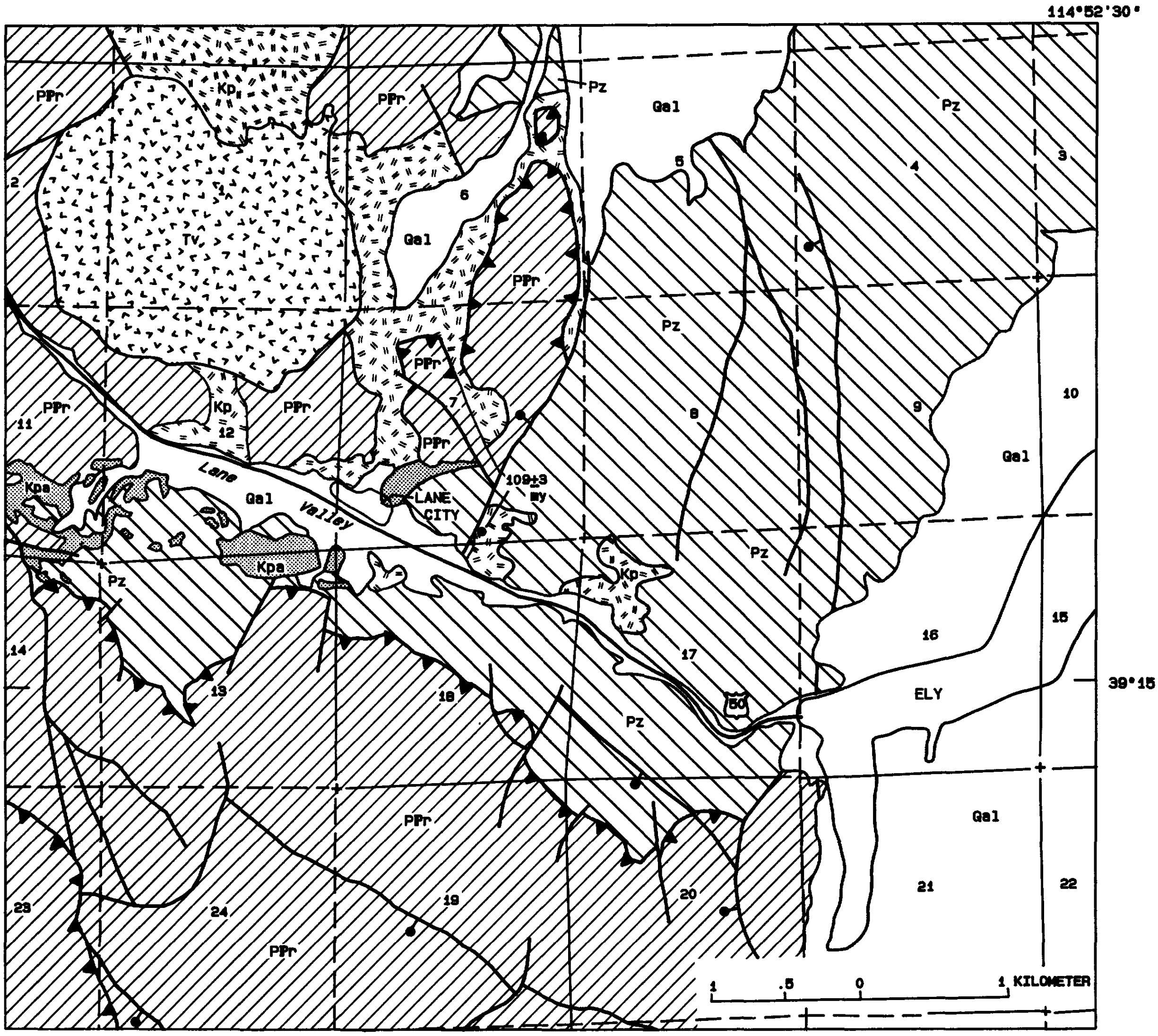
Figure E15 (above and facing page). Generalized geology of the Ely copper mining area, and adjacent gold-producing area to the east, modified from Gott and McCarthy (1966), Brokaw (1967), Brokaw and Barosh (1968), Brokaw and others (1973), and Brokaw and Heidrick (1966). Plutons, many of them mineralized with disseminated sulfide minerals, and two major sedimentary rock groups are outlined. Faults, including post-ore extensional (Basin-Range-type) faults, are shown. The areas surrounding the plutons consist of complexly faulted Paleozoic sedimentary rocks and Tertiary volcanic rocks. Potassium-argon age data for samples are from McDowell and Kulp (1967) and Beal (1957).

production figures have not been released, but it is estimated from production rates and averages that the district produced more than 3 million oz of gold in the period 1900–1978. (Appendix provides more data.)

Exploration drilling during the 1960's, 1970's, and 1980's by Kennecott, the operator of the copper mines, and their exploration subsidiary Bear Creek Mining Co., delineated bodies of low-grade gold-mineralized rock on the flanks of the Ruth porphyry copper ore body. Gold-bearing pyrite zones also were identified and drilled in the vicinity of the Saxton and other old gold mines of the district. Silver King Mines, Inc. leased the Kennecott properties in 1985. Currently the Star Pointer ore body, which crops out a short distance south-southwest of the old production shaft for the Ruth copper mines, is operated as an open pit mine feeding a cyanide plant. Smith and others (1988) described this deposit in detail. Reserves at the end of 1986 were stated as 1.65 million tons of ore assaying 0.13 oz Au/ton (British Petroleum Co., financial summary, 1986) and about 1 million tons of low-grade ore assaying 0.03 oz Au/ton (Smith and others, 1987). Available data indicate a low silver content.

Acknowledgments

Encouragement from and discussions with many geologists formerly of Kennecott Copper Corporation,



EXPLANATION

Qal — Quaternary alluvium (Cenozoic)

Tv — Tertiary volcanic rocks, predominantly rhyolite (Cenozoic)

Kp — Cretaceous quartz monzonite porphyry (Mesozoic)

Kpa — Cretaceous quartz monzonite porphyry, altered (Mesozoic)

PPr — Permian and Pennsylvanian sedimentary rocks (Paleozoic)

Pz — Pre-Pennsylvanian sedimentary rocks (Paleozoic)

Contact

Normal fault--Symbol on downthrown side

Thrust fault--Teeth on upper plate

109+3 (M-K) — Location of dated sample; K-Ar age in millions of years; (M-K), McDowell and Kulp (1967); (B), L.H. Beal (written commun., 1957) including C.H. Phillips, J.C. Wilson, R.L. Nielsen, J.E. Welsh, W.R. Wilson, J.S. Vanderpool, G. Westra, and H.D. Kreis are especially appreciated. W.R. Wilson, M. Smith, and J. Benham of Silver King Mines, Inc. provided a tour of recent developments. Reviews by S.C. Potter, R.F. Hardyman, and D.R. Shawe improved this paper. Collaboration with A.W. Rose of The Pennsylvania State University and Chi-I Huang, now of FMC Corporation, aided in the work. Several libraries and private collections yielded old unpublished reports on inaccessible mines. The Nevada Mines Division of Kennecott, a subsidiary of Standard Oil of Ohio, owner of the property, permitted publication of this paper. The writer, however, bears responsibility for all conclusions.

GEOLOGIC SETTING

Folded Paleozoic marine sedimentary rocks and Cretaceous igneous rocks host the ores of the Ely district. The general stratigraphic sequence is as follows:

Permian:	Arcturus Formation
	Rib Hill Sandstone
	Riepe Spring Limestone
Pennsylvanian:	Ely Limestone
Mississippian:	Chainman Shale
	Joana Limestone
Mississippian-Devonian:	Pilot Shale
Devonian:	Guilmette Limestone

These rocks are described in detail by Hose and others (1976). Pre-ore décollement faulting juxtaposed Permian-Pennsylvanian and pre-Pennsylvanian rocks (fig. E15), and tectonically thinned some units in parts of the district. Cretaceous quartz monzonite porphyry bodies, with which gold and copper mineralization was associated, intrude all these rocks (McDowell and Kulp, 1967). Intensely altered porphyry and adjacent sedimentary rocks contain the economically mineralized ground of the district. A mid-Tertiary sequence of extrusive and locally intrusive volcanic rocks perforates and caps the older sedimentary rocks and Cretaceous porphyry bodies. No metallic mineralization is known to have been associated with the younger igneous rocks.

The sedimentary sequence is generally unmetamorphosed except near the Cretaceous intrusions. Where the ore deposits are localized, nearly all pre-Tertiary rocks show evidence of hydrothermal alteration (fig. E15). As documented by James (1972; 1976) and Westra (1982), post-ore extensional faulting has sliced the system into a series of blocks which can be restored to a pre-fault configuration. The quartz monzonite intrusions grade upward from a propylitically altered core to a potassically altered, strongly mineralized porphyry copper system. Figure E17 shows this gradation. The potassic zone grades upward successively into a sericitic zone and then a zone of advanced argillic alteration, following the classification of Meyer and Hemley (1967). Alteration in adjacent shale included the development of extensive hornfels aureoles adjacent to altered intrusive rocks, as well as potassic to propylitic alteration similar to that in the intrusions. Shale host rock adjacent to fresh or propylitically altered intrusions shows considerably fewer effects of alteration.

Structure and Igneous Rocks

The porphyry copper bodies and their calc-silicate aureoles are cut by low- to moderate-angle Basin-Range type faults (fig. E15). These faults disrupted an originally elongate, more compact porphyry copper system that had a vertical extent of perhaps 1,000 m (James, 1976). A remarkable cross section through the mineralized part of the system and its weakly altered and pyritized root zone is thus exposed. The gold-rich top of the system (fig. E16) lies to the east, whereas its deepest part is north of the westernmost open-pit mines. With the district restored to its pre-Basin-Range geometry, the mineralized porphyry system yet retains an east-west elongation.

The fundamental pre-ore structural elements of the system are two:

1. A west-trending deep-seated linear structure.
2. A system of low-angle décollement faults, probably contemporaneous with the Sevier orogeny (Cretaceous), into which the quartz monzonite bodies were intruded. The faults, some of them almost flat, are post-Permian and pre-intrusion.

Both structural elements contributed to the east-west elongated form of the original pluton(s), and to the elongate shape of the narrow precious-metal mineralized aureole that surrounds it. Second-order structures of multiple azimuths and ages are abundant. The Star Pointer gold deposit is localized in the hanging wall of a fault that strikes N. 60° E. (fig. E19) and dips 60° NW. The strike of the fault is radial to the Ruth porphyry copper ore body. Smith and others (1988) described pre- and post-ore movement on this structure.

Highly mineralized, potassically altered quartz monzonite porphyry is locally intruded by unmineralized quartz monzonite. K-Ar ages on biotite from the mineralized quartz monzonite porphyry average 110 Ma; the K-Ar age on hornblende from the unmineralized quartz monzonite is 103 Ma (McDowell and Kulp, 1967, p. 907). The ages of initial intrusion and mineralization appear to be approximately the same; and mineralization had ceased before intrusion of unmineralized quartz monzonite a few million years later. The Star Pointer gold deposit lies in the general vicinity of both intrusive rock types, but it most probably predated the unmineralized quartz monzonite.

Hydrothermal Alteration

The siliceous dolomitic limestone units (notably the thick Ely Limestone) adjacent to the mineralized porphyry bodies record mineralogically and economically spectacular hydrothermal alteration. Adjacent to propylitically altered and non-altered intrusive rock, a zone of fine-grained diopside and minor green-tinged andradite-grossularite garnet extends less than 1 m from the contact. Pyrite grains are present at one locality as are scheelite crystals. Adjacent to potassically altered and mineralized quartz monzonite bodies, the Ely Limestone contains a wide aureole of colorful calc-silicate skarn (or tactite) minerals, veined by quartz and sulfide minerals. James (1976) referred to this aureole as the tactite zone. Above the tactite zone, adjacent to altered porphyry containing predominantly quartz, sericite, and pyrite, limestone is replaced by fine-grained quartz, green saponite clays, and pyrite. A surficial oxidation of this rock type produced jasperoid-like silica bodies. Few published data compare gold content of calc-silicate rocks with jasperoids and other silicified rocks within areas mined for copper.

With some restoration of post-ore faulting, and assumption of a generally homogeneous siliceous magnesian limestone in contact with a single major intrusion of porphyry, a generalized tabulation of primary alteration assemblages in limestone and porphyry can be made:

In porphyry	In adjacent limestone	Position
Advanced argillic?	Advanced argillic: zunyite and gibbsite in aluminous rocks. Local gold-bearing silica bodies.	Near-surface, largely eroded or mined.
Quartz-sericite: strongly silicified, pyrite-rich.	Silica-pyrite zone: quartz, pyrite, copper sulfide minerals, and nontronite replace much limestone.	Extends well below supergene zone. Disseminated gold in calcareous sandstone.
Relict biotite in strongly veined silicified porphyry.	Relict skarn minerals, nontronite-saponite, epidote, and siderite.	Hypogene copper± gold ore.
Biotite-orthoclase alteration assemblage: secondary biotite and orthoclase veining in less silicified porphyry; plagioclase relicts rimmed by orthoclase.	Skarn or tactite zone: massive garnet, diopside, and magnetite; veins of actinolite sulfide minerals, quartz and nontronite-saponite.	Hypogene ore extends well below supergene zone.
Propylitic assemblage–relict plagioclase and chlorite; local areas of intense magnetite metasomatism.	Quartz-magnetite rock, geometry not well known; low content of sulfide minerals.	Beneath known ore.
Almost totally unaltered equigranular porphyritic monzonite–quartz monzonite.	Bleached limestone with narrow aureole of anhydrous skarn minerals.	Beneath ore and distant from mineralized porphyry.

Einaudi (1982) presented a comparison of this zoning with other skarn deposits.

Presence of an advanced argillic alteration assemblage (including gibbsite, zunyite, kaolinite, and abundant pyrite) in several gold-rich deposits above silicic intrusive bodies has been noted, for example at Summitville, Colorado (Steven and Ratté, 1960), and Chin-Qua-Shih, Taiwan (Folinsbee and others, 1971; Yen, 1976). In both these deposits, the gold content of veins sharply decreases with depth, as advanced argillic alteration features disappear. Sillitoe (1983), Carlile and Kirkegaard (1985), and James (1984) described the relationship of gold-rich enargite–advanced argillic assemblages to deeper or adjacent porphyry copper-mineralized bodies in the Philippines and Indonesia.

Westra (1982, p. 956–964) described quartz-sericite, biotite-orthoclase, and calc-silicate hornfels alteration of the Chainman Shale adjacent to mineralized porphyry in the Ruth pit. He described the east (Ruth) end of the district as a cupola formed atop a large stock. Garnetiferous, sulfide-bearing skarns occur in the Joana Limestone, and Pilot Shale has been converted to hornfels. Jasperoid breccias, noted in siltstone-shale horizons of the Pilot Shale near gold deposits elsewhere in the region, have not been identified.

The rocks with the highest gold values at the Ruth porphyry deposit are near the top of the present exposures, in silica-rich rocks in the vicinity of advanced argillic mineral occurrences. Erosion and pyrite decomposition have destroyed some of the original features. The distribution of trace gold peripheral to the Ruth deposit (fig. E16; Gott and McCarthy, 1966) is much more strongly anomalous than adjacent to porphyry deposits in the western part of the district.

ORE DEPOSITS

The metamorphic-metasomatic aureole surrounding the porphyry intrusions has yielded between 80 and 87 million tons of copper ore (Bauer and others, 1964, and my projections), mainly from the tactite zone. The gold content of this ore has not been reported separately from that produced from porphyry ores. The metamorphic-metasomatic aureole (fig. E17) consists of several facies of alteration types, cut by multiple stages of veining. In the Veteran, Tripp, and at least the deeper half of the east end of the Liberty pit, skarns contained economic quantities of copper, as described by Bauer and others (1964) and by James (1976). Bauer and others (1964) noted that ore-grade material in altered limestone "extends up to 500 feet [150 m] from the porphyry contacts, but the average is probably 200 feet [60 m]." In

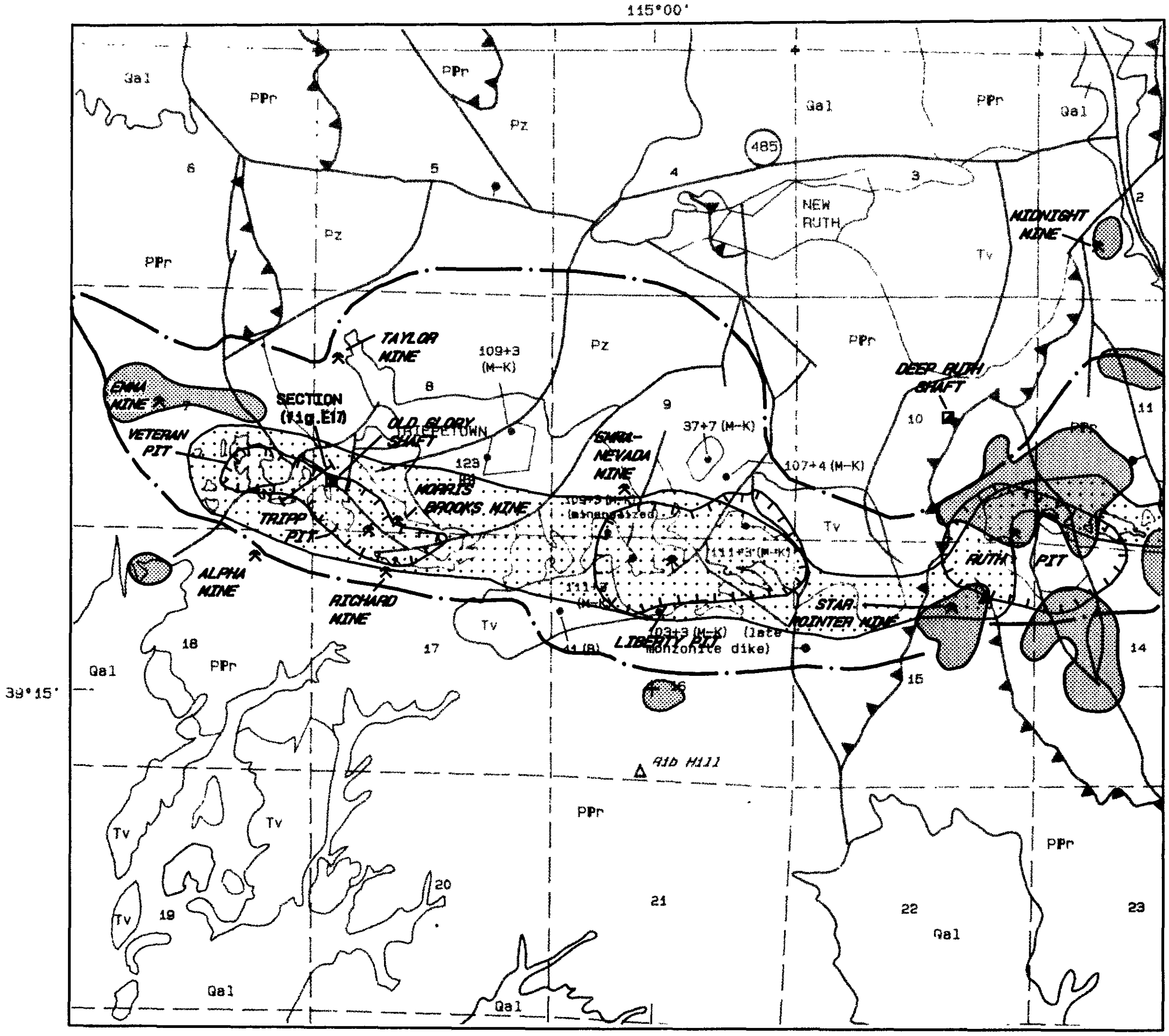


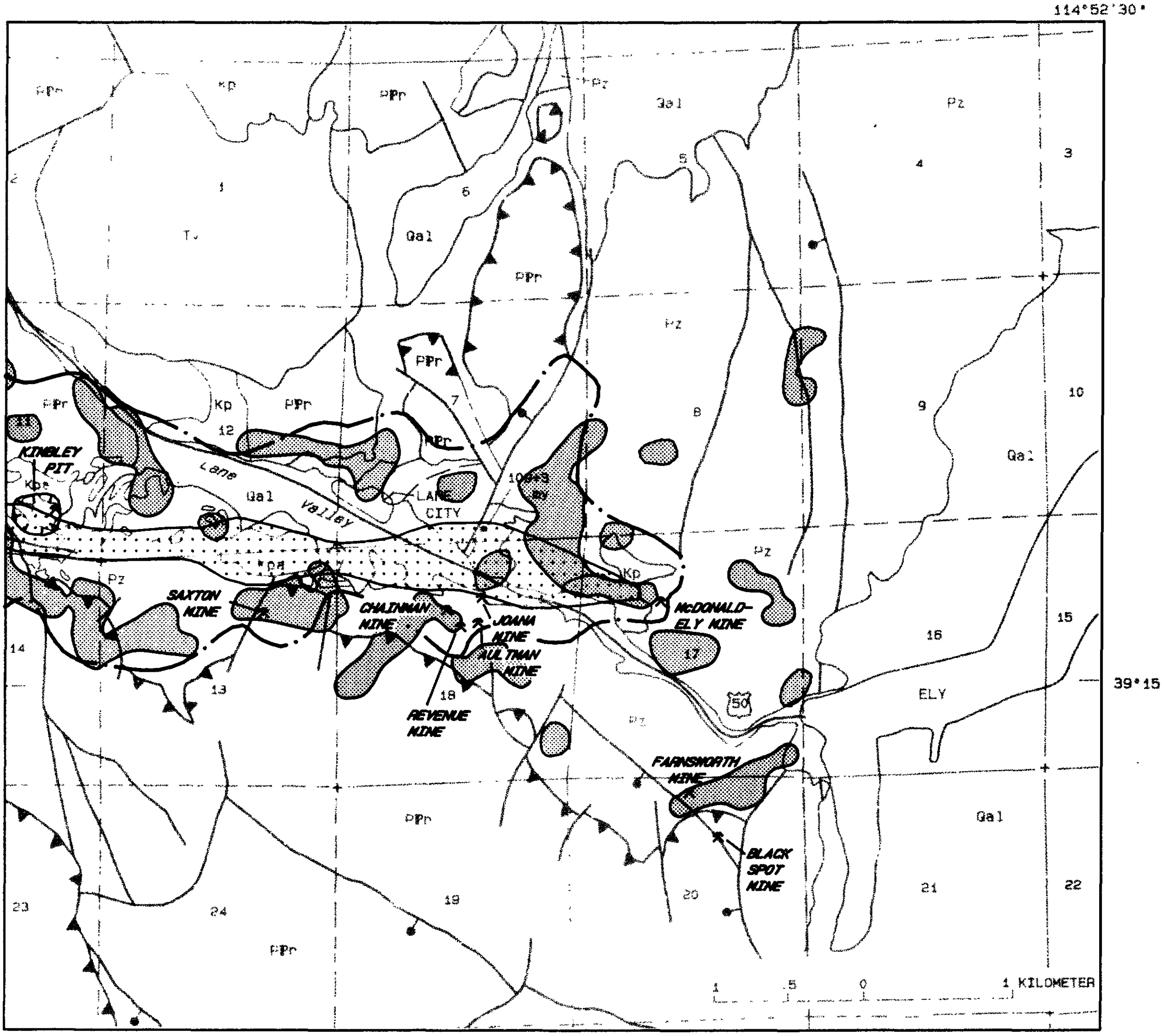
Figure E16 (above and facing page). Ely district, showing intensely altered ground, copper- and gold-mineralized areas, and mine locations. Line of section locates figure E17.

places, ore-grade primary copper in limestone occurs adjacent to much lower grade mineralized porphyry. In contrast, Westra (1982) determined that only insignificant tonnages of ore-grade material exist in the 150–210-m-wide skarn aureole in the Ruth pit. The few nonproprietary data available on gold content of limestone ores indicate erratic, or very complex, variation of gold content of mineralized limestone.

The gold content of mineralized porphyry given in the reports just cited generally ranges from 0.15 to 0.5 ppm or 0.004 to 0.015 oz Au/ton. Substantially higher values are reported in calcareous Rib Hill Sandstone atop mineralized porphyry. At least local modification of gold distribution near the surface, by supergene enrichment and leaching, or residual enrichment, is suspected. Copper was strongly enriched here. The behavior of gold in the acid supergene environments near oxidizing pyritic porphyry bodies is not understood.

The Star Pointer gold deposit (figs. E18, E19) is believed to be hosted in one of the thick calcareous quartz-sandstone units in the Rib Hill Sandstone, at least 700 ft above its base (Smith and others, 1988). Fault-controlled hydrothermal breccia is associated with ore (Durgin, 1989). Gold shows preferential concentration in strongly silicified sandstone locally containing as much as a few percent black specularite or carbonlike material of uncertain origin. No visual correlation of mineralized sandstone with calc-silicate minerals is observed.

A number of pyritic gold occurrences in the eastern part of the district are hosted by much older strata. Structure and general proximity to intrusions are probable ore controls.



EXPLANATION

—·— Generalized boundary of intensely altered area within which most rocks are silicified and enriched in iron (from Gott and McCarthy, 1966; in part from Spencer, 1917)

Generalized area within which mineralized samples contain 0.5 percent Cu or more (from Gott and McCarthy, 1966)

Generalized area within which mineralized samples contain 0.00875 oz Au/ton or more (0.3 ppm Au or more) (from Gott and McCarthy, 1965)

Mine

Shaft

Open pit

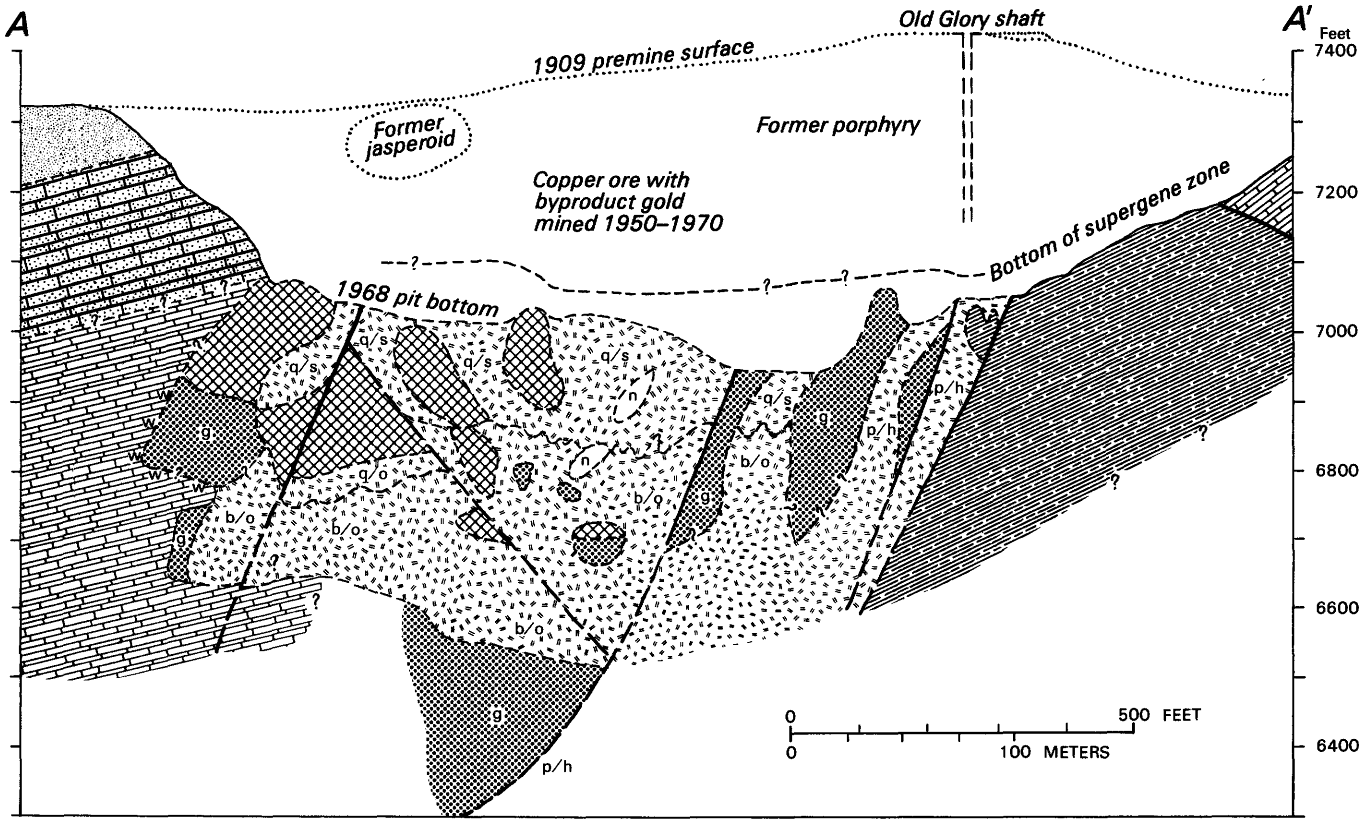


Figure E17 (above and facing column). Cross section through the northwest end of the Tripp porphyry copper pit, southwest of New Ruth, Nev., showing nature of intrusion and related altered rock that comprise the mineralized porphyry and skarn of the district. Section is viewed N. 42° W.; it passes immediately northwest of the Old Glory Shaft, an early copper mine described by Spencer (1917); no vertical exaggeration. Extrapolation of data from Bauer and others (1964) indicates that about 40 million tons of ore was produced from this pit before closure (owing to slope failures) in 1969–1970. The section, modified from James (1972), is based on drill-hole data and mapping during mining, 1968–1970. Contacts and units queried where uncertain. In Cretaceous quartz monzonite porphyry, q/s is quartz-sericite alteration assemblage, almost all of hypogene origin; contains quartz veinlets and 5–10 percent pyrite; q/o is transition between quartz-sericite alteration assemblage and biotite-orthoclase alteration assemblage; b/o is biotite-orthoclase alteration assemblage (flooding and veining), with 2–3 percent pyrite and about 1 percent chalcopyrite; p/h is propylitic alteration assemblage, possibly of a younger intrusive phase, in which plagioclase and hornblende are little altered. In Pennsylvanian Ely Limestone, w is wollastonite that occurs as a selvage against tactite alteration zone; n is transition between silica-pyrite and tactite alteration zones and also is a selvage against quartz-sulfide veinlets; tactite alteration zone assemblage varies with dolomite content of the host unit and degree of local iron or magnesium metasomatism; in the Tripp pit the assemblage is normally diopside plus quartz, veined by actinolite plus quartz, plus sulfide minerals or magnetite; g is andradite garnet plus quartz and sulfide minerals or magnetite, a variant of the tactite zone most common in the Liberty pit.

EXPLANATION

Cretaceous quartz monzonite porphyry

Permian Rib Hill Sandstone

Permian Riepe Spring Limestone—Pyritized

Pennsylvanian Ely Limestone

Silica-pyrite alteration zone in Ely Limestone

n — Nontronite or iron saponite after actinolite and diopside in Ely Limestone

Tactite alteration zone in Ely Limestone

Mississippian Chainman Shale

—?— Contact—Queried where uncertain

Fault—Dashed where projected

Table E13. Gold and silver content (recovered) of copper ores, Ely, Nevada

[Calculated from metal production figures. Recovery by flotation process in 1920's approximated 70 percent of the gold, and 90 percent of the copper (U.S. District Court testimony, no. F-157, *in* Parsons, 1957). In later decades, when more oxidized and low-grade ores from limestone were processed, copper recovery is known to have decreased. S (1947), unpublished 25th annual report of Consolidated Coppermines Corporation, New York, 1947, 20 p.; **, direct smelting ores; no mill recovery loss incurred; ***, average grade produced from mine; ---, no data]

Year(s)	Mine(s) and (or) ore type	Au (oz/ton)	Ag (oz/ton)	Cu (percent)	Cu:Au ratio	Sources and comments
1909-1910	Porphyry ores	0.00096-0.019	0.037-0.045	2 (about)	26,000	Spencer (1917), "20 to 40 cents in gold"; also, production to 1915 (Spencer, 1917, table, p. 98).
1908-1935	All mines; mainly porphyry.	.0093	.031	1.11	31,700	Bateman (1935, p. 309).
1943	Emma Nevada, Morris, Brooks, underground, mainly porphyry.	.01	.020	.824	74,900	S (1947, p. 6). Average copper recovery was 87.8 percent, gold 69.5 percent, silver 61.2 percent.
1943	Richard (850-ft level).	.002**	.016**	4.73***	627,740	S (1947).
1943	Taylor	.047**	1.318**	4.99***	28,350	S (1947). Minor tungsten also produced.
1943	Tonopah (West Liberty pit), porphyry.	.006	.015	.74***	33,630	S (1947). West end, Liberty pit.
1947	Brooks, Morris, mainly porphyry.	.009	.018	.79***	23,320	S (1947, p. 10). Average copper recovery was 79.7 percent, gold 52 percent, silver 55 percent.
1947	Tonopah (West Liberty pit), porphyry.	.004	.015	.68***	45,120	S (1947).
1947	Richard, underground.	.003**	.035**	4.35***	39,500	S (1947).
19??	Consolidated Coppermines (probably Emma, Morris, Tonopah).	.0175***	.043***	---	(low)	S (1947). Average of 15 samples assayed from a composite of mill-head samples collected over a period of 8 days, per court records.
1986-87	Star Pointer gold	.13	Low	Low	---	Smith and others, 1988. Copper "slightly enriched relative to fresh country rocks"; Au:Ag=4:1 in cyanide mill solution.

Characteristics of Gold Ores

The character of the porphyry ores and that of adjacent calc-silicate copper ores, which have yielded most of the gold in the district, have been well described by Bauer and others (1966), Fournier (1967), and James (1976). Chalcopyrite is the main primary mineral, and is replaced by chalcocite and locally by covellite. The distribution of gold within these ores can be calculated only from production data, which include losses attendant to milling of ore. Table E13 presents available data on gold content. Hose and others (1976) stated that the average gold content of ores in the Ely district is 0.0076 oz Au/ton, apparently of recoverable gold.

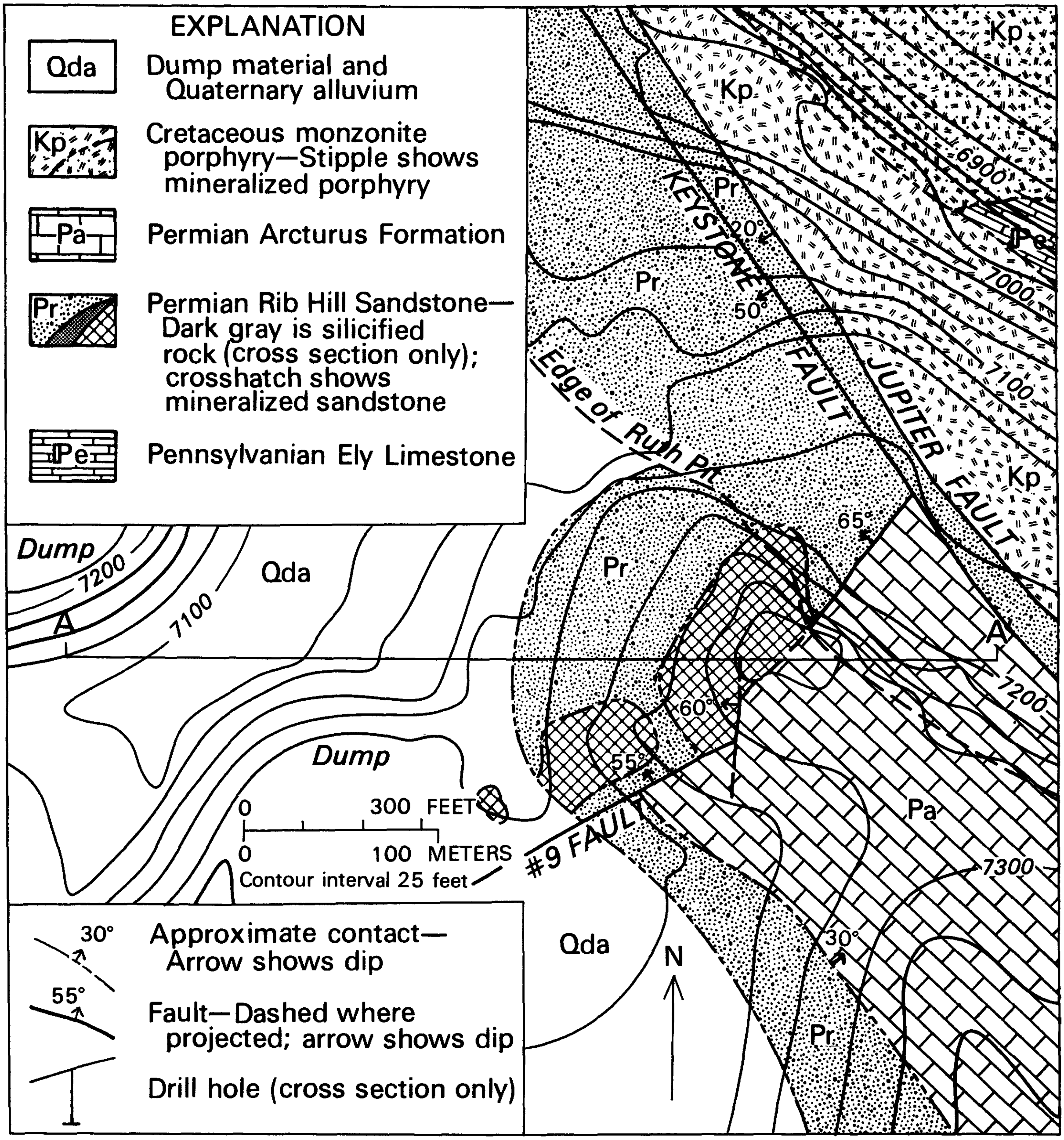


Figure E18. Generalized geology of the Star Pointer disseminated gold deposit (modified from Smith and others, 1988). Cross section is shown on figure E19.

The most significant variations in gold content (based on published data) are between the typical open pit and underground porphyry-calc-silicate ores and the ores from the Richard mine area. The Richard and Alpha underground mines, located south of the west end of the belt of mineralized plutons (figs. E15, E16) produced high-grade oxide, carbonate, and native copper ores. The main ore minerals were delafossite ($CuFeO_2$) and azurite. As indicated in table E13, these ores were unusually low in gold. These deposits are believed to have been fossil exotic copper occurrences, emplaced where paleodrainage from the main porphyry bodies entered favorable sedimentary rock units. Correlation of data presented by Kesler (1973, p. 107) with data from areas mined in 1968–1970 indicates that rock from the Tripp-Veteran pit area probably assayed higher in gold than rock from the east end of the Liberty pit.

The principal porphyry-calc-silicate ore deposits of copper at Ely are generally high in gold compared to the Laramide (Late Cretaceous–early Tertiary) porphyry copper bodies of the southwestern U.S. (Kesler, 1973). Copper deposits at Bisbee, Ariz., of Jurassic age and at

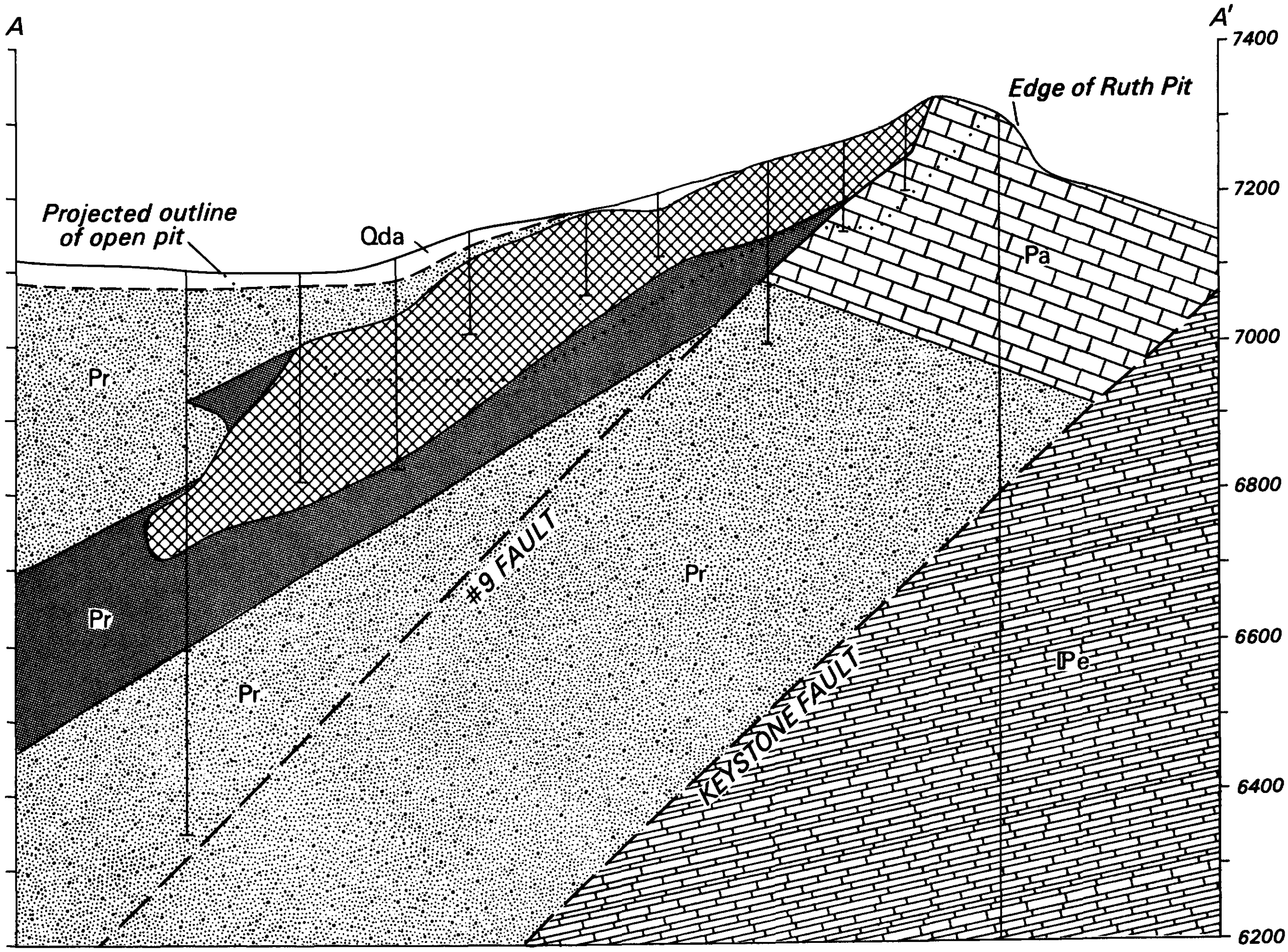


Figure E19. Generalized cross section showing interpreted geology of the Star Pointer gold deposit (modified from Smith and others, 1988). Data mainly from drill holes by Kennecott Copper Corporation and Silver King Mines Company. Symbols explained on figure E18.

Bingham, Utah, of Oligocene age both have high gold contents, also. Both these deposits also were emplaced in calcareous sedimentary sequences. The reasons for the high gold contents of these deposits remain speculative. Possibilities include a host rock of greater regional (metallogenic) gold content, an evolution of the porphyritic igneous rocks more conducive to gold concentration, and a more alkaline environment for gold transport allowing a higher gold content in mineralizing fluids.

The mineralogy of gold in the copper ores at Ely is not well understood. Microscopic examination of several dozen polished sections of massive and disseminated copper ore failed to reveal gold, but many higher grade gold ores worldwide also rarely show metallic gold in random section. As table E13 indicates, all the reported gold was recovered during flotation, where the intent was to recover chalcopyrite and chalcocite and depress the maximum amount of pyrite. Metallurgists also noted minor gold concentrations at low spots in the mill circuit (gravity concentration of free gold). Eilers (1914) noted that the metallic copper produced from the Ely ores in the early years of operations had a very low tellurium content, compared with that obtained at Bingham, Utah, of 5.5 lbs/ton. On the basis of these relations, gold in the primary ores probably occurs within chalcopyrite and as fine-grained free gold; that which remained encapsulated in quartz or pyrite or for other reasons did not "float" with the copper sulfide minerals was not recovered. The copper content of most ores from the center of the district is more than 23,000 times the gold content (table E13). Veinlets containing free gold were not recognized during mining at Ely, as they have been in some porphyry districts.

The small ore bodies outside the zone of major copper deposits are less well exposed for study. Some, such as at the Taylor mine north of the Tripp pit area (table E13), have a high content of copper sulfide minerals. Most lie to the east of the copper-rich part of the district, and are thoroughly oxidized at the surface.

Mining company records indicate very minor production of gold from small vein systems west and south of the open pit mines. Samples of oxidized veinlets, jasperoids, and silica boxworks contained anomalously high amounts of gold, silver, tellurium, and mercury, notably from areas as far east as the western edge of the town of Ely (Gott and McCarthy, 1966). Ores from the Black Spot–Farnsworth mines in this eastern area, localized in Joana Limestone just beneath Chainman Shale, have no known base metal content. The recorded production and reserves of these mines are of bedded deposits as much as 6 m (20 ft) thick that contain 0.12 oz Au/ton (4 ppm Au) and 5.8 oz Ag/ton (200 ppm Ag).

At the Chainman-Aultman-Joana group of mines west of the Black Spot–Farnsworth mines and on the south side of Lane Valley, ore is localized in the basal part of the Chainman Shale near its contact with the underlying Joana Limestone. The mineralized bed, which does not crop out, dips shallowly to the south. The limestone is strongly impregnated with limonite, and exhibits mineralized karstlike features. In the Chainman and other mines, the ore above water level was "porous, honeycombed quartz, which in places was so soft as to be almost sand***undoubtedly formerly containing sulfides" (unpublished report by H. Krumb on Chainman Consolidated Mining Company, Ely, Nevada, to William Boyce Thompson, February 6, 1913). These gossan ores, shipped as flux to smelters, locally carried from 0.5 to 5 oz Au/ton. Spencer (1917, p. 172) reported samples collected by the mine operators that contained 0.04–0.14 oz Au/ton and from 20 to 50 percent Fe. A 1907 unpublished company map shows the bottom, or 240-ft, level as having "an excess of sulphides." The adjacent Revenue mine had similar gold-silver gossan ore in a bed of the Joana Limestone. The Aultman mine was noted for a relatively high silver content (>2 oz Ag/ton).

The Saxton gold mine lies between the Kimbley pit and the Chainman mine (fig. E16; Spencer, 1917). It is in Mississippian-Pennsylvanian sedimentary rocks near the south contact of a pyritized argillized monzonite pluton. The intrusion contains no known chalcopyrite ore, but it appears to contain local chalcocite perhaps of supergene origin. Sandy beds in the Chainman Shale and adjacent limestone have been thoroughly replaced by white quartz and pyrite, accompanied by gold, in the footwall of a décollement or thrust fault. Old stopes follow a N. 70° E. fracture zone. Most production came from a high-grade oxidized spongy silica (unpublished 1931 report by E.N. Pennebaker on gold deposits on properties of Consolidated Coppermines Corporation). Coarse subhedral pyrite is the major sulfide mineral noted in primary protore here.

Gold produced from the McDonald-Ely (Robust) mine was from a vertical pyrite-rich vein and from jasperoids; this mine was also noted for base metal showings (Spencer, 1917, p. 176). The mineralized ground here occurs near a small granitic stock characterized by large pink orthoclase phenocrysts. Adjacent to one of the gold-copper veins, silicate minerals in limestone include micas.

According to A.V. Heyl (oral commun., 1985) a small amount of high-grade gold ore (about 0.25 oz Au/ton) was produced in about 1956 from a breccia pipe in Ely Limestone at the Midnight mine east of New Ruth. The siliceous gold-bearing core of the pipe was surrounded by a shell containing oxide-zinc minerals.

Exploration drilling for copper in deeper Mississippian and Devonian rocks beneath the porphyry system has failed to reveal substantial gold deposits.

Ore Fluids

Fluid inclusions in garnet, pyroxene, and quartz from the Ely copper deposits were studied by Huang (1976) and Huang and others (1978) using a heating stage. Fluid inclusions in minerals from the tactite zone have homogenization temperatures of 450–600 °C, and are dominated by liquids. Crosscutting quartz-sulfide veinlets surrounded by argillically altered rock showed a wide range of salinities, as much as 42 weight percent NaCl equivalent, and varied temperatures, suggesting multiple generations of veining. Silicified limestone overlying the calc-silicate rocks of the tactite zone contains vapor-rich inclusions, suggesting that boiling occurred here. No data were obtained on advanced argillic alteration minerals. Goss (1983), studying fluid inclusions within and below the Ruth deposit, found little or no evidence of early magma-related fluids in deep unaltered igneous rocks and minor associated quartz veins.

Huang (1976) and Huang and others (1978) also analyzed carbon and oxygen isotopes from the zone peripheral to the porphyry copper bodies. In traverses inward from unaltered limestone to marble, they determined a systematic decrease in $\delta^{18}O$, suggesting the effect of magmatic water. The $\delta^{18}O$ values are higher for calcite than for coexisting quartz, suggesting isotopic disequilibrium.

Using calculated fractionations for water, Huang and others (1978) determined a temperature of 660–360 °C for formation of quartz-magnetite pairs from the clay-sulfide veinlets. They also found, in the tactite zone of the Veteran pit, that calculated $\delta^{18}O$ compositions of ore fluids decreased regularly from $+10.5$ per mil at the center of the intrusion to $+7$ per mil at its periphery.

CONCLUSIONS

Substantial amounts of gold have been produced from the Ely district because very large tonnages of copper ore with minor gold content have been produced, and because much of the contained gold was recoverable with the copper. Gold mines in the periphery of the district, most probably lying in the outer zones of the same copper system, have to the late 1980's yielded a smaller production, although gold grades in these zones are actually higher than in the porphyry copper deposit itself. Rocks from a few leached, silicified outcrops may have produced high-grade silver gold ores for early miners, but were most significant as indicators of copper ores, concealed below. Unknown quantities of gold-bearing capping rock were stripped off during copper mining. A potential remains for discovery of deposits similar to the Star Pointer ore body.

The Ely copper deposits differ from many porphyry and skarn systems in the United States in their higher gold content, greater age, and elongate form. Gold distribution within the Ely system approximates that of other gold-rich porphyry systems with overlying advanced argillically altered, high-sulfide ore zones, described by Sillitoe (1983). Gold deposition accompanied a major enrichment in sulfur, copper, and probably iron and silica, in and adjacent to the apex of the cooling quartz monzonite body. Westra (1979, 1982) and Huang and others (1978) suggested that hydrothermal fluids, of magmatic origin during early stages of ore formation, entered fractured but still hot porphyry beneath the west end of the district, and passed upward and eastward toward the top of the system. A cap of argillically altered silicified rock containing a substantial concentration of gold probably characterized the upper and outlying parts of this large hydrothermal system.

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APPENDIX—1990 UPDATE

A 1,200 ton/day cyanide mill in the district became operational Oct. 1, 1986. The mill, currently owned by Alta Gold Co. in partnership with Echo Bay Group, produced 123,416 oz Au through March 31, 1989, including production from heap leaching operations begun in 1988. Silver King Mines, Inc.–Pacific Silver Corp. (1989) reported proven and probable diluted reserves of minable gold ore at the Star Pointer, plus a number of other smaller deposits within its land-holdings in the district, to be 2,250,000 tons of 0.089 oz/ton mill ore and 43,750,000 tons of 0.016 oz/ton heap leach ore. These reserve figures include a calculation for dilution resulting from waste that will have to be processed with the ore. Some dump material, removed mainly from the Ruth pit area, has been determined to be of leachable grade. Durgin (1989) noted that additional tonnages of low-grade copper-gold porphyry ore are not presently economic, and are not considered as reserves.

Durgin (1989) described several of the smaller deposits included in the above figures. The recently opened Northwest Ruth deposit, at the northwest corner of the former Ruth copper pit, is in Riepe Spring Limestone and Rib Hill Sandstone. Here, intrusive breccia invaded a northeast-trending complexly faulted zone. Rather erratic silicification was controlled by faults and favorable lithologies. Gold commonly is coarse (to 0.02 mm) and not everywhere associated with silica. In contrast to Star Pointer gold ore, pyrite and fluorite are locally abundant, silver content is much higher, and some gold is present in quartz veinlets. Limited data show lead, copper, and zinc exceed 0.1 percent, selenium and tellurium are as high as 50 ppm, and arsenic ranges between 50 and 100 ppm (Durgin, 1989).

Silver King Mines, Inc.–Pacific Silver Corp., 1989, Prospectus/Proxy statement: Salt Lake City, p. 60–66.

The Tomboy-Minnie Gold Deposits at Copper Canyon, Lander County, Nevada

By Ted G. Theodore, Stephen S. Howe, *and* David W. Blake[1]

Abstract

The Tomboy-Minnie gold deposits are part of a middle Tertiary porphyry copper system whose central porphyry body is centered at Copper Canyon. Gold-silver ores in the Tomboy-Minnie deposits occur mostly in a pyrrhotite- and pyrite-rich basal 30-m-thick sequence of altered calcareous conglomerate in the Middle Pennsylvanian Battle Formation. The Tomboy-Minnie deposits are distal contact-metasomatic gold deposits that are characterized by actinolite- and chlorite-dominant assemblages in marked contrast to the skarn, potassium silicate, and phyllic assemblages that characterize copper-gold-silver deposits closer to the central porphyry stock. Introduction of gold occurred penecontemporaneously with replacement of early diopside alteration assemblages by actinolite and chlorite. Metals are zoned strongly in the system: A proximal copper-gold-silver zone grades outward to a gold-silver zone (in which lie the Tomboy-Minnie deposits), which in turn is succeeded by a distal lead-zinc-silver zone. The entire mineralized system contained a minimum of about 3.3 million ounces of gold before large-scale mining operations began.

INTRODUCTION

Mining in the Battle Mountain mining district, about 19 km southwest of the town of Battle Mountain, Nev., spans a period of more than 120 years, from 1866 to the present. However, the first large-scale attempt to mine base and precious metals by open-pit methods was begun by Duval Corporation in 1967. Prior to that time, the Copper Canyon underground mine (fig. E20) had been operated sporadically between 1917 and 1955 (Roberts and Arnold, 1965). Placer gold was discovered in Copper Canyon in 1912, and intermittent small-scale placer operations were carried on into the early 1940's. From 1944 to 1955, Natomas Company operated a dredge on the alluvial fan at the mouth of Copper Canyon and reportedly produced 100,000 oz of gold (Johnson, 1973, p. 37–38). The closely spaced Tomboy-Minnie deposits, first described by Blake and others (1978), were placed into operation as copper reserves declined in the nearby West ore body (Theodore and Blake, 1975; 1978).

[1]Battle Mountain Gold Exploration, Battle Mountain, Nev.

History of Reserves and Mine Development

Ore reserves in Duval's East ore body (fig. E20) in Copper Canyon prior to the 1967 start-up included 13,875,000 tons containing 0.79 percent Cu, along with 0.025 oz Au/ton and 0.47 oz Ag/ton (Sayers and others, 1968, p. 56). The deposit has since been mined out (Theodore and Blake, 1975). The West ore body was developed subsequent to the depletion of the East ore body, and contained approximately 4 million short tons of ore at grades generally similar to those in the East ore body (Theodore and Blake, 1978). The Tomboy-Minnie deposits contained an estimated 3,900,000 short tons of ore grading 0.09 oz Au/ton and 0.28 oz Ag/ton (Anonymous, 1981). The Tomboy-Minnie deposits were mined out during late 1982, and precious-metal mining operations were shifted to an area immediately surrounding the Independence Mine (fig. E20), which is referred to as the Northeast Extension deposit just north of the East ore body.

In 1981, Duval Corporation announced discovery of a large gold-silver skarn ore body, the Fortitude, just north of the West ore body in the Copper Canyon area. Initial mining reserves for the Fortitude deposit were stated to be 16 million tons containing 2.4 million oz of gold and 9.2 million oz of silver (Anonymous, 1981). Subsequent reserve studies for the Fortitude deposit predicted that the same amount of precious metals was contained in approximately 12 million tons (Wotruba and others, 1986).

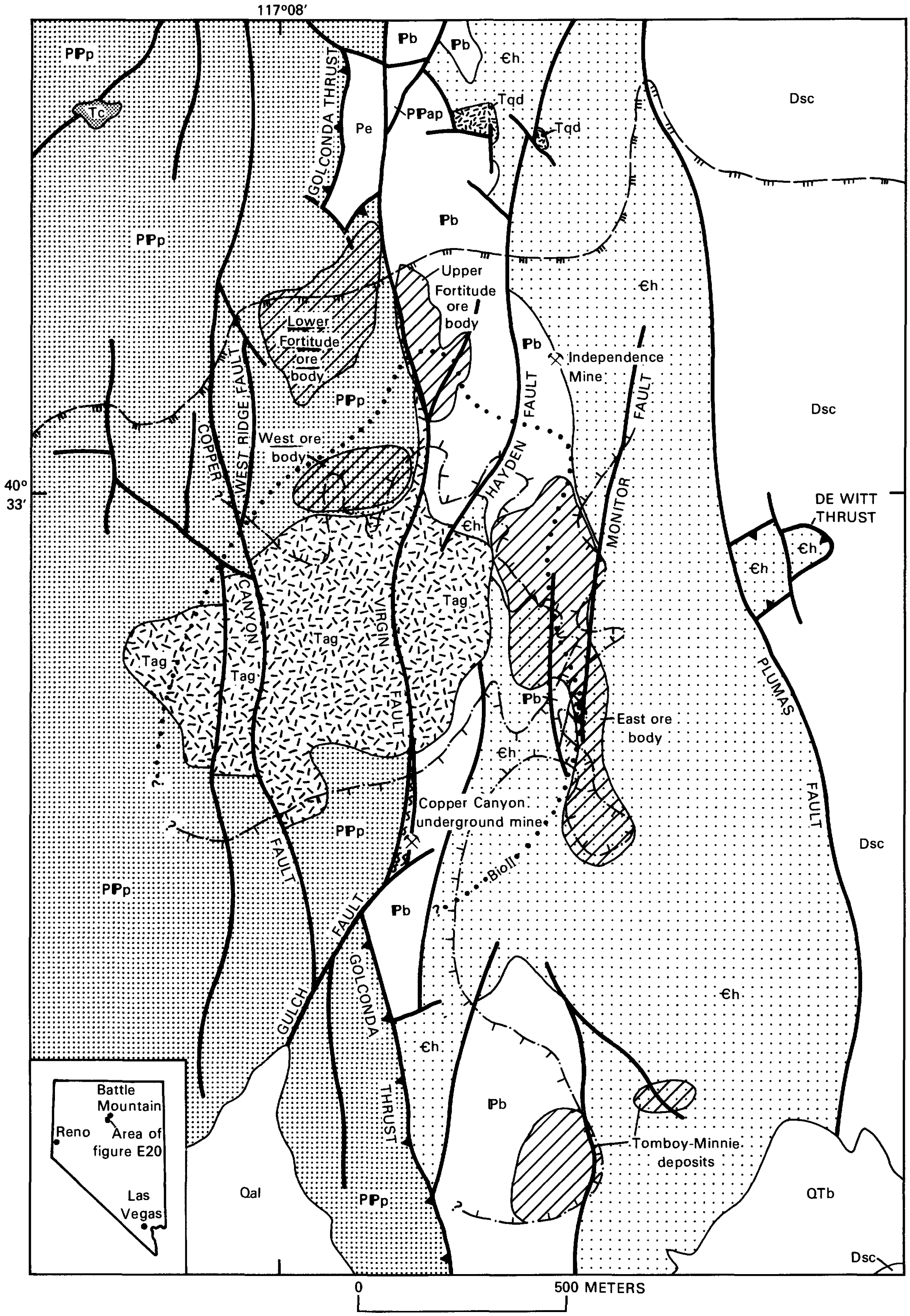
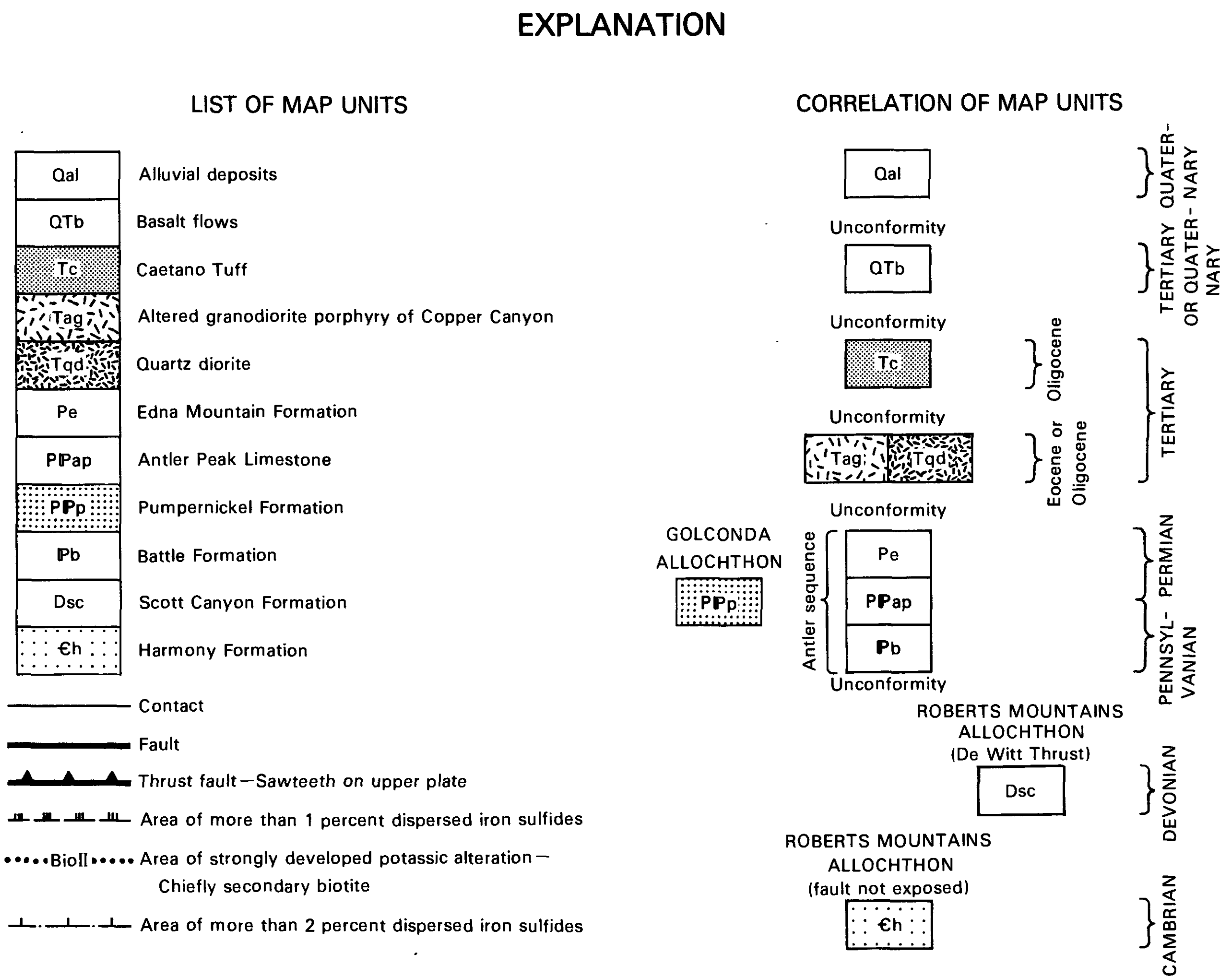


Figure E20 (above and facing page). Geologic sketch map of Copper Canyon area, Lander County, Nevada.



On January 1, 1985, the board of directors of Pennzoil Company, parent of Duval Corporation, announced the formation of an independent company, Battle Mountain Gold Company, as a spin-off to the shareholders of Pennzoil Company. This announcement occurred subsequent to a previous announcement by Pennzoil Company that all of Duval's metal-mining operations were up for sale (Epler, 1985). In 1986, Battle Mountain Gold Company confirmed existence of a gold deposit in Copper Basin northeast of Copper Canyon, termed the Surprise (Argall, 1986). Estimated reserves for the Surprise Mine include 160,000 oz of gold in 1.75 million tons of ore (Anonymous, 1986), and production from the Surprise Mine commenced during the third quarter of 1987 (Anonymous, 1987).

Ore Processing

Milling of copper-gold-silver ores, mostly from the East and West ore bodies at Copper Canyon (Theodore and Blake, 1975; 1978), continued to 1977, when minable copper-gold-silver ores there were exhausted. Copper production from 1967 to 1975 in the Battle Mountain mining district ranked third in the State behind operations at Yerington and Ely, both presently (1988) suspended. Leaching operations in the Battle Mountain district, centered mostly in the Copper Basin area, resulted in the largest production of copper in the State of Nevada in 1981 (Lockard and Schilling, 1983). The mining operation at Copper Canyon shifted to the processing of gold-silver ores in January 1979, initially in large part from highly sulfidized replacement ore bodies at the Tomboy-Minnie deposits (Blake and Kretschmer, 1983; Theodore and others, 1986). Existing plant facilities at Copper Canyon were modified at this time to include cyanide leach and carbon-in-pulp adsorption sections for processing of gold-silver ores (Jackson, 1982).

Metal Production

Metal production from the district to 1961 included 150,000 oz of gold, 2.1 million oz of silver, 15,000 tons of copper, 5,000 tons of lead, and 1,500 tons of zinc. Duval's production from both milling and leach-precipitation operations at Copper Canyon and nearby Copper Basin for the period 1967–1974 was 102,082 tons of copper (Theodore and Blake, 1975, p. C2).

During 1980 and 1981, production of gold from ore bodies in the Copper Canyon area contributed significantly toward making Nevada the leading gold-producing State (Lockard and Schilling, 1983; Lucas, 1982). Gold-silver production in 1980–1984 from the Copper Canyon area included the following (Prospectus, issued by Battle Mountain Gold Company, July 12, 1985):

	1980	1981	1982	1983	1984
	(Tons and oz expressed in thousands)				
Tons ore milled	1,068	1,234	1,400	1,291	1,231
Stripping ratio	3.95:1	6.31:1	9.32:1	12.06:1	17.26:1
Mill feed (oz Au/ton)	0.073	0.064	0.059	0.072	0.071
Recovery factor, Au (pct.)	87	85	85	87	85
Oz gold recovered	69	66	71	80	73
Oz silver recovered	21	39	92	307	357

In addition, through December 1984, recovery of precipitates of copper from leach dumps at both Copper Canyon and Copper Basin continued at a rate of approximately 2,400,000 lb copper per year.

Estimated full-scale production from the Fortitude mine of 150,000 oz of gold per year was anticipated to be reached in 1985. Production in 1985 from the Fortitude mine actually amounted to 220,000 oz of gold and 647,000 oz of silver (Argall, 1986), and in 1986, 259,000 oz of gold and 964,000 oz of silver (Northern Miner, Feb. 23, 1987, p. 24).

Significance of Skarn-Associated Gold Systems

Gold skarn systems in the Battle Mountain mining district, including the Tomboy-Minnie distal contact-metasomatic gold deposits, and gold skarns in the McCoy mining district, approximately 30 km south of Copper Canyon, define a cluster of such deposits that are similar in age, 35–38 Ma, but hosted by rocks in different tectonic blocks. The gold skarns in these districts seem to have developed in successively higher tectonic blocks near the southern limit of the cluster as it is presently known.

The Fortitude and McCoy gold deposits are parts of two world-class gold skarn systems (Orris and others, 1987). The importance of this gold-mineralized environment in north-central Nevada is evidenced further by the announcement by Echo Bay Mines that it had discovered an additional 4 million oz of gold at its Cove deposit, which apparently occurs in Triassic limestone and conglomerate on the fringes of its McCoy gold skarn deposit (Echo Bay Mines, Special Report to Stockholders, December 23, 1987). Thus, the Battle Mountain and McCoy mining districts probably contained about 10 million oz of gold in known deposits prior to the onset of large-scale mining operations. For comparison, along a 72-km stretch of the northwest-trending Carlin mineralized belt, which occurs approximately 50 km east of the Battle Mountain mining district, about 27 million oz of gold are known to occur in 21 sediment-hosted gold deposits (The Northern Miner, November 16, 1987, p. A28).

GEOLOGIC SETTING OF THE COPPER CANYON DEPOSITS

A geologic sketch map of the Copper Canyon area, based on mapping by Roberts (1964), Theodore and Blake (1978), and Wotruba and others (1986), shows the location of the copper-gold-silver West and East ore bodies and the gold-silver deposits of the Northeast Extension, the Tomboy-Minnie and the Fortitude deposits (fig. E20). All these deposits consist of replacement-disseminated sulfide ore, within Paleozoic sedimentary rocks.

The Paleozoic sedimentary and minor volcanic rocks of the Copper Canyon area underwent several stages of deformation, including major thrust faulting during the middle Paleozoic Antler orogeny and early Mesozoic Sonoma orogeny, and Basin-and-Range block faulting and intrusive activity during the Tertiary (Roberts, 1964). Rocks belonging to the Early Mississippian Roberts Mountains thrust system include sandstone, shale, and minor limestone of the Upper Cambrian Harmony Formation, which have been thrust along the DeWitt thrust over chert, minor volcanics, and limestone of the Devonian Scott Canyon Formation. The DeWitt thrust is an imbricate fault related to the Roberts Mountains thrust system. Disconformably overlying the Harmony Formation are coarse clastic rocks and limestone of the autochthonous Antler sequence, which includes the Middle Pennsylvanian Battle Formation, the Pennsylvanian to Permian Antler Peak Limestone, and the Permian Edna Mountain Formation. These formations of the Antler sequence host the bulk of the precious and base metals at Copper Canyon. Above the Antler sequence are chert and argillite of the Pennsylvanian to Permian Pumpernickel Formation, which were transported tectonically eastward into this area along the Golconda thrust fault during the early Mesozoic Sonoma orogeny (Silberling and Roberts, 1962; Speed, 1977).

Precious and base metal deposits in the Copper Canyon area of the Battle Mountain mining district are genetically and spatially related to a middle Tertiary (Theodore and others, 1973) altered granodiorite porphyry that has intruded the sequence of Paleozoic sedimentary and volcanic rocks (fig. E20). The contact metamorphic aureole associated with this stock extends several hundred meters into its wallrocks. Most base and precious metal ore at Copper Canyon occurs as replacement and disseminated sulfides in originally calcareous rocks that have been metamorphosed and metasomatically altered to various calc-silicate assemblages including skarn (Theodore and Blake, 1978). Ore occurs locally in noncalcareous rocks as disseminated sulfide minerals, veinlets, and fissure veins. Hydrothermal silicates and sulfide minerals are distinctly zoned about the stock, a relation that contributed significantly toward the recognition and development of additional ore reserves in the Copper Canyon area.

During late Eocene or early Oligocene time the porphyritic granodiorite stock intruded the sequence of Paleozoic sedimentary and volcanic rocks at Copper Canyon. The stock contains phenocrysts of quartz, plagioclase, potassium feldspar, and biotite set in a mosaic, microaplitic groundmass of quartz, potassium feldspar, and biotite. Detailed petrographic studies of this stock show that its modal composition overlaps the quartz monzonite–granodiorite compositional field of Bateman (1961). Locally rare hornblende phenocrysts occur in deep parts of the stock. Potassic alteration assemblages that include widespread secondary biotite are predominant throughout most of the altered granodiorite porphyry of Copper Canyon.

TOMBOY-MINNIE GOLD DEPOSITS

The geology of the Tomboy-Minnie gold deposits is relatively simple (fig. E21). Although unconformable elsewhere in the district, bedding in both the Battle Formation and the underlying Harmony Formation strikes generally north and dips about 30° W. in the Tomboy pit. Shale and siltstone of the Harmony Formation have been converted to brown biotite hornfels during emplacement of the porphyritic granodiorite of Copper Canyon, whereas the fine-grained matrix of sandstones (including quartzarenite, subarkose, and litharenite) was recrystallized and silicified to clay minerals, white mica, and secondary quartz. In the Copper Canyon area, the Battle Formation consists of three members with a total thickness of about 250 m (Wotruba and others, 1986). A relatively small, complexly faulted, downdropped sliver of the lower member of the Battle Formation is exposed in the Minnie pit. A much greater thickness of the lower member of the Battle Formation is exposed in the Tomboy pit, where it is as much as 100 m thick (Roberts, 1964; Theodore and Blake, 1975). The lower member of the Battle Formation in the Tomboy pit may be divided into two units (not shown on fig. E21) based on primary lithology, and hydrothermal metallization. Gold mineralization was restricted mainly to a basal 30-m-thick unit of calcareous conglomerate that is replaced by calc-silicate-mineral assemblages with a high content of sulfide minerals. Typically, this basal sequence is dark greenish black in contrast to the lighter colored rocks of the Battle Formation higher in the lower member. The upper part of the lower member contained less calcareous material and upon metallization yielded a much lower sulfide content. In the Tomboy-Minnie deposits, most of the basal 30-m-thick sequence of the conglomerate in the Battle contains subangular to subrounded, framework-supported clasts of chert, quartzite, and lesser limestone. Thin limy siltstone and shale beds are also interbedded with the basal calcareous conglomerate. Generally, the upper 70 m of the Battle Formation in the Tomboy pit is conglomerate with a matrix of quartzose sandstone made of tightly interlocked grains of quartz and lithic fragments. Locally, near the top of the Battle, there are several beds that are generally less than 1 m thick and consist almost entirely of actinolite-tremolite.

In the Tomboy-Minnie deposits an early diopside assemblage is replaced successively by actinolite- and chlorite-bearing assemblages, each of which was accompanied by iron sulfide minerals and free gold. Veins are absent from the ore zones in the basal 30 m of conglomerate in the Battle. The matrix, formerly calcareous and in places showing traces of relict carbonate, now consists of either (1) an actinolite-dominant assemblage that also includes quartz, plagioclase, sphene, minor chalcopyrite and epidote, and traces of potassium feldspar and apatite; or (2) chlorite-dominant assemblages containing quartz, clays, pyrrhotite and (or) pyrite, chalcopyrite (minor), epidote, sphene, and relict actinolite and diopside. Galena and sphalerite are abundant in shaly parts of the deposit, and are complexly intergrown with pyrrhotite and minor chalcopyrite, yielding a "banded" aspect to metasomatized rocks. Textural relations in chlorite-pyrite-rich ores suggest that the pyrite, which contains rare microscopic blebs of galena, is paragenetically somewhat later than pyrrhotite, sphalerite, early-stage galena, chalcopyrite, and arsenopyrite (trace).

A north-trending granodiorite porphyry dike crops out along the east wall of the Minnie open pit and is shown schematically in a cross section through the deposits (fig. E21). North of the Minnie pit, this dike is well exposed in a roadcut, and dips steeply to the west. The dike is composed of quartz, plagioclase, and biotite phenocrysts set in a microaplitic groundmass of potassium feldspar, quartz, plagioclase, and minor biotite. This

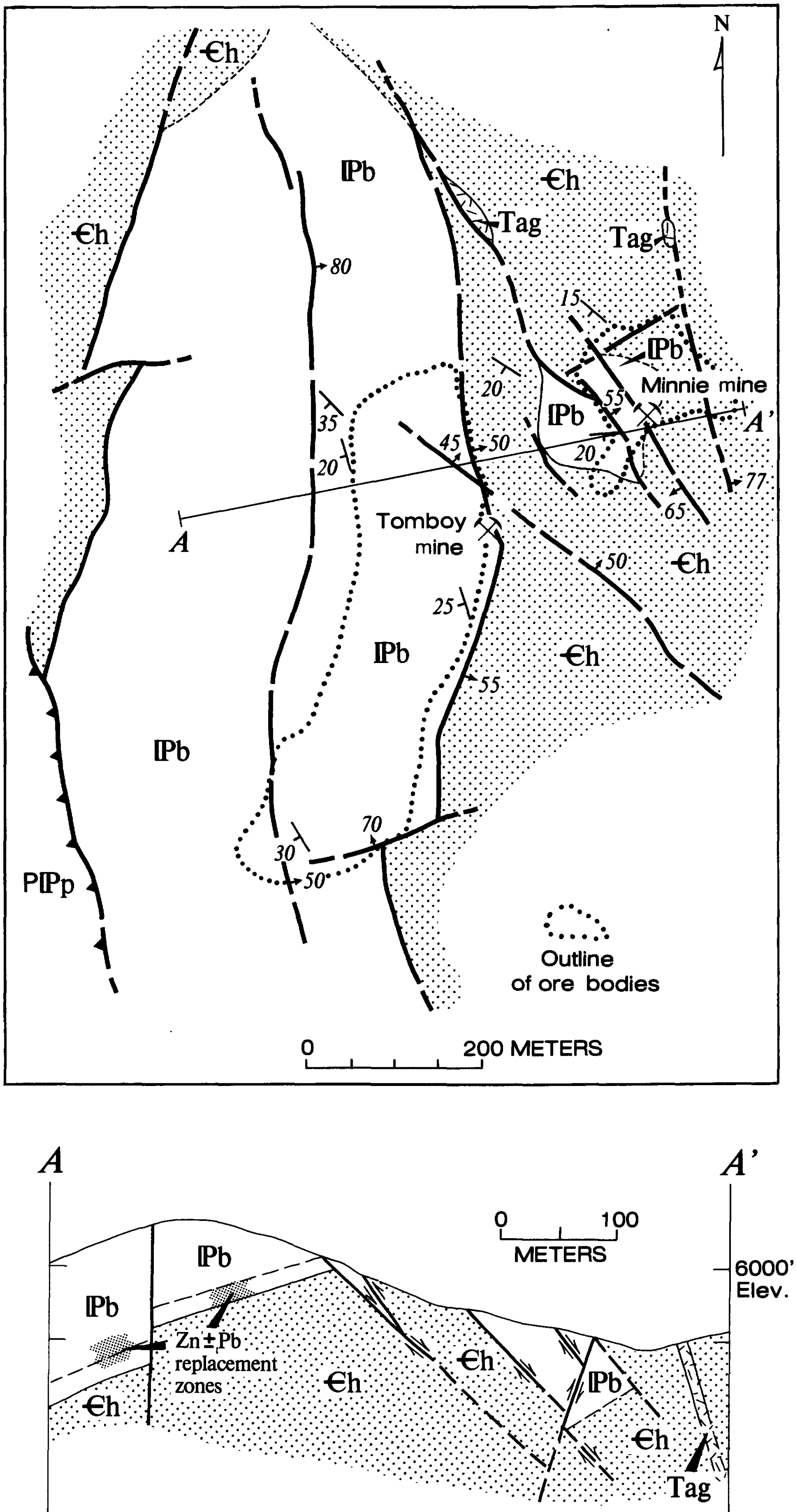


Figure E21. Generalized geologic map and cross section *A–A'* of Tomboy-Minnie area, Lander County, Nevada. Tag, altered granodiorite of Copper Canyon; PIPp, Permian-Pennsylvanian Pumpernickel Formation; IPb, Pennsylvanian Battle Formation; €h, Cambrian Harmony Formation. Heavy lines, faults; dashed where inferred. Sawteeth on upper plate of thrust. Dip of faults and strike and dip of bedding are shown. On cross section arrows show direction of movement on faults.

dike is similar petrographically to the potassically altered granodiorite of Copper Canyon. Locally, however, the dike has been enriched in gold and silver in its more altered parts.

The Tomboy-Minnie gold deposits occur within an alteration zone, termed transitional by Blake and others (1978), that contains more than 4 volume percent total sulfide minerals, in contrast to rocks outside this zone, which have generally 2 volume percent or less total sulfides. Alteration in the deposits resulted from a combination of early, mostly isochemical, thermal metamorphism followed by metasomatism. Thermal effects resulted in the calcareous basal conglomerate of the Battle Formation being converted to a quartz + diopside + epidote hornfels assemblage. Sparse garnet replaced some limestone clasts. Secondary quartz is generally present, except in thin lenses that consist entirely of actinolite-tremolite. Actinolite-dominant assemblages and chlorite-plus-minor-clay assemblages were formed contemporaneously with sulfide mineralization and the ore-forming stage. Some chlorite occurs as a replacement of earlier formed calc-silicate minerals. Epidote is more common near the base of the Battle Formation than higher in the sequence; epidote is also concentrated along fractures in the underlying Harmony Formation directly below the unconformity. Hydrothermal alteration in the Harmony Formation caused development of clay adjacent to some veinlets, replacement of phyllosilicate matrix by clay, and introduction of very sparse quartz-sulfide veinlets. Limited studies of these veinlets show that they contain sulfide-mineral assemblages similar to the replacement-disseminated assemblages in the overlying Battle Formation.

Premineral and postmineral faults were important in the development of these deposits. The Minnie deposit has been offset approximately 200 m below the level of the Tomboy deposit along a series of northwest-striking, east-dipping postmineral normal faults (fig. E21). A west-dipping, northwest-striking reverse fault has offset these east-dipping, low-angle normal faults. Just west of the Tomboy deposit, a nearly vertical north-striking fault locally has dropped the Battle Formation about 30 m to the west. Many minor northwest-striking, high-angle faults and fractures of small displacement are premineral throughout both deposits, and they served to enhance access of hydrothermal solutions and the deposition of sulfide minerals.

Sulfide content in these ore bodies ranges from 10 to more than 50 volume-percent and is mostly pyrrhotite and pyrite. Locally, however, marmatite and galena are abundant in podlike replacement bodies shown schematically in figure E22. Figure E22 is a N.-45°-E. schematic section through the deposits prepared from geologic and assay data obtained from 19 percussion drill holes along the section line. Samples from each 1.5- or 3-m (5- or 10-ft) drill-hole interval were analyzed for silver, gold, copper, lead, and zinc. However, only silver, gold, and zinc assays are shown, and the lower limits of assays used to depict the distribution of each metal are based on ore-grade calculations and background geochemistry for deposits elsewhere in the district; they are 0.10 oz Ag/ton, 0.050 oz Au/ton, and 500 ppm Zn. Other sulfide minerals in the Tomboy-Minnie deposits, in decreasing abundance, include marcasite (replacing pyrrhotite), chalcopyrite, and arsenopyrite. Trace arsenopyrite occurs in rare quartz veinlets in the deposits. Chalcopyrite locally increases with an increase in pyrrhotite and is most abundant near the base of the Battle Formation.

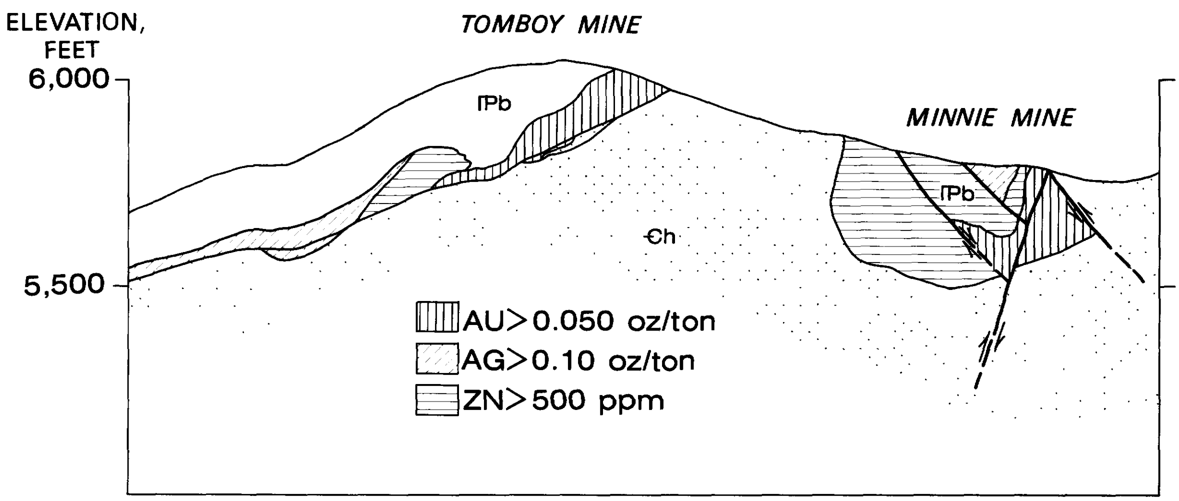


Figure E22. Idealized northeast-trending cross section through the Tomboy-Minnie deposits showing rocks containing >0.05 oz Au/ton, >0.10 oz Ag/ton, and >500 ppm Zn. Data taken from 19 percussion drill holes along the trace of the cross section. ℙb, Pennsylvanian Battle Formation; Ꞓh, Cambrian Harmony Formation.

Gold has not been observed in microscopic examination of the Tomboy-Minnie deposit ore. However, statistical evaluation of assays of drill-hole samples suggests that gold is closely associated with pyrrhotite and pyrite. Free gold, generally less than 0.05 mm diameter, was recovered during the milling of ore from these deposits; this relation suggests that some gold occurs in the native state as discrete grains together with pyrrhotite and pyrite. Free gold in the East ore body was in larger particles than that mined in the Tomboy and Minnie deposits, and typically was very strongly associated with sulfide-bearing quartz veins. Silver in the Tomboy and Minnie deposits correlates closely with galena. Studies at Duval's laboratory in Tucson, Ariz., have shown that native silver has exsolved from galena. Silver content also may be related, in part, to overall sphalerite content.

The Tomboy and Minnie gold deposits in Copper Canyon have not been dated. Based on the general zonation of these gold deposits relative to the altered granodiorite porphyry of Copper Canyon, we believe the time of gold deposition of the deposits to be similar to that of the East ore body, which was determined as 37 Ma, using the potassium-argon method on fine-grained secondary biotite in the Battle Formation (Theodore and others, 1973).

METAL ZONING AND AU:AG RATIOS

Roberts and Arnold (1965) recognized a zonal distribution of metals in the Battle Mountain district. At Copper Canyon, their zonal distribution of metals has been modified on the basis of more recent data. The zonal distribution of metals based on assays of samples from open-pit mining operations and drill holes is shown in figure E23. Nearly all the data reflect metallization hosted by the Battle Formation, except for that associated with the andradite- and diopside-rich skarn assemblages in the West ore body (Theodore and Blake, 1978). The metals are zoned strongly outward from the altered granodiorite porphyry of Copper Canyon. A proximal copper-gold-silver zone gives way outward to a gold-silver zone, which in turn is succeeded by a distal lead-zinc-silver zone. The granodiorite porphyry at the center of these metal zones contains anomalous but subeconomic amounts of copper, molybdenum, gold, and silver. The zone containing economic concentrations of copper, gold, and silver at the West and East ore bodies is located within the mapped outer limit of potassic alteration (Blake and others, 1978). However, the West ore body also shows significant modification of early andradite- and diopside-bearing assemblages by tremolite- and actinolite-bearing assemblages. Sulfide minerals in the copper-gold-silver zone include pyrrhotite, pyrite, chalcopyrite, and lesser quantities of sphalerite, galena, marcasite, and arsenopyrite. The gold-silver zone typified by the Fortitude, Northeast Extension, and Tomboy-Minnie deposits is situated between the copper-gold-silver and lead-zinc-silver zones. The Tomboy-Minnie deposits, however, are also associated spatially with some locally high concentrations of lead and zinc. The precious metal zone results from an especially high concentration of gold- and silver-bearing sulfides, mostly pyrrhotite and pyrite, that are disseminated and had replaced the calcareous matrix and lenses of the lower Battle Formation. The outermost zone contains a significantly lower overall content of sulfide minerals and is dominated by galena and sphalerite typically as veins. In addition, some major north-striking, pre-metallization faults at Copper Canyon affected the overall distribution of metals by providing conduits that allowed metal-depositing fluids to move beyond the limits of the replacement zones of mineralization.

Metal zoning of the deposits on a local scale apparently occurs at the Tomboy deposit, where proximal high concentrations of gold are followed outwards by increased abundances of zinc and silver (fig. E22). In addition, such a zoning pattern of increased zinc and silver towards the northwest is a reversal of the overall zoning pattern that surrounds the altered granodiorite porphyry of Copper Canyon. This zoning pattern was established by prior geochemical studies of the Tomboy-Minnie deposits (Blake and Kretschmer, 1983) which showed that gold assays of samples from the first interval of drill holes and soil samples best outlined the deposits; lead and zinc concentrations increased in a zone peripheral to each deposit. Because the Tomboy-Minnie deposits may be considered to be distal contact-metasomatic gold deposits, these deposits should exhibit their own metal zonation (Sillitoe, 1983, p. 54). Also, it is possible (as we will discuss further) that these two precious metal deposits might be genetically related to a hypabyssal igneous body separate from the main intrusive body at Copper Canyon.

Figure E22 diagrammatically shows that gold concentrations greater than 0.050 oz Au/ton are restricted to the high sulfide-bearing rocks near the base of the Battle Formation. The thickest section of gold-bearing conglomerate occurs under the ridge crest near the original Tomboy discovery and in the tectonically depressed fault blocks of the Battle Formation in the Minnie deposit. In the Tomboy deposit, this gold-bearing conglomerate extends down dip for about 200 m, following the unconformity that separates the Battle and Harmony Formations. At 200 m, the zone of high gold mineralization thins out and grades into a zone that shows zinc mineralization and that contains more than 500 ppm Zn. Here the zinc mineralization formed pod-

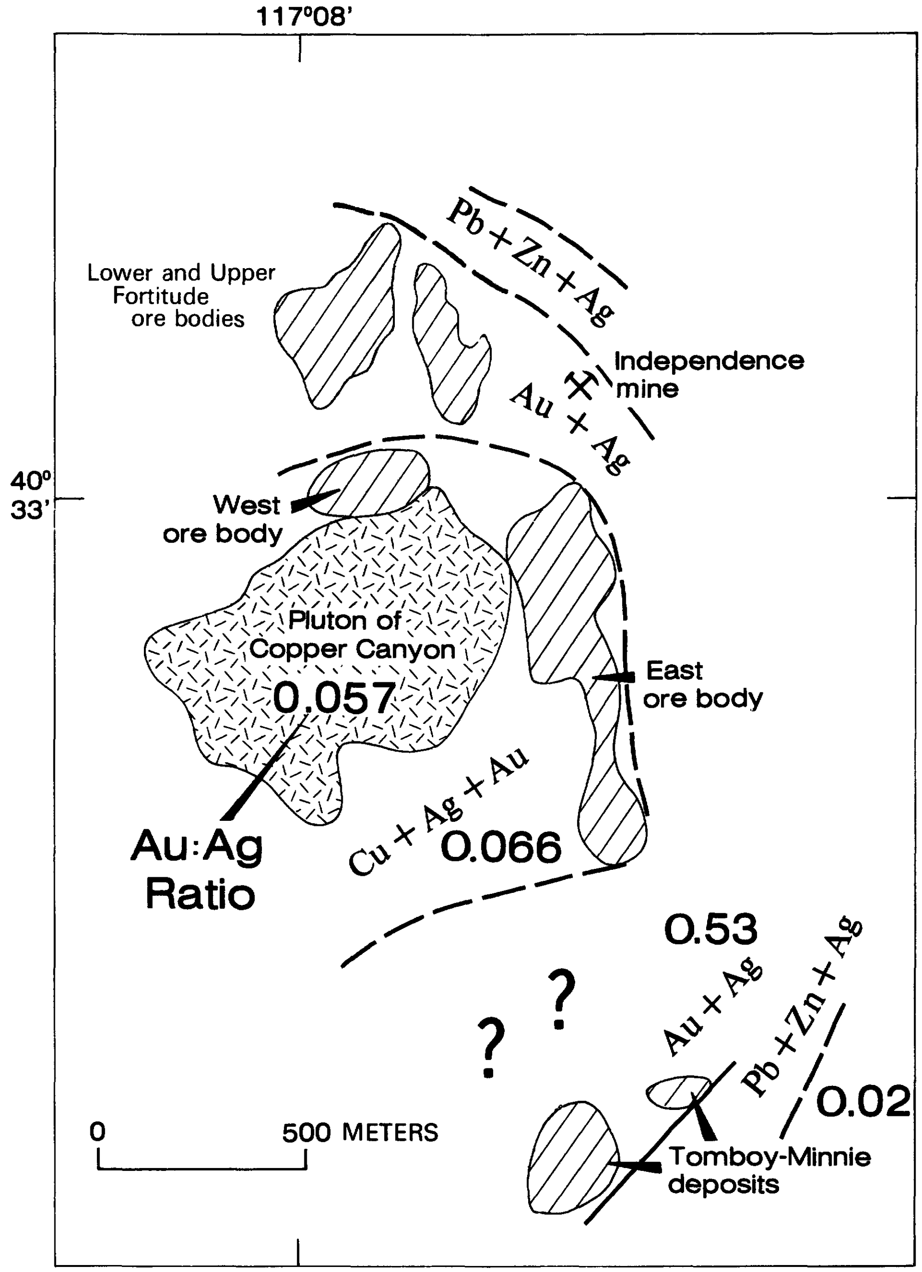


Figure E23. Zonal distribution of metals and Au:Ag ratios in the Copper Canyon area.

like bodies and replacement lenses that slightly overlap the gold zone. Overall contents of sulfide minerals in the thin distal parts of the gold zone are less than that in the thick parts of the gold zone. Sphalerite also occurs in the Harmony Formation below the main gold zone at the Tomboy deposit. At the Minnie deposit, zinc mineralization was extensive in the Harmony Formation, where sphalerite is localized primarily in the breccia along northwest- and northeast-striking faults.

The outermost metal zone recognized at the Tomboy-Minnie deposits is represented by silver assays greater than 0.10 oz Ag/ton. Sphalerite and galena also occur within this zone. In the Tomboy deposit, silver mineralization occurred in an 18- to 25-m-thick tabular body at the base of the Battle Formation. As was the case with the gold and zinc zones, the silver and zinc zones show a slight overlapping. A remnant of the silver zone is preserved in the Minnie deposit; all three metals apparently are zoned vertically in one and the same fault block of Battle Formation.

The three metal zones described at the Tomboy-Minnie deposits are characterized also by significantly different abundances of silver, lead, and zinc. Average values for each metal zone are:

	Ag (oz/ton)	Pb (ppm)	Zn (ppm)
Au zone	0.06	40.0	155.0
Zn zone	0.11	160.0	1,855.0
Ag zone	0.22	800.0	2,320.0

The high lead and zinc contents of the silver zone reflect isolated pods and replacement lenses of sphalerite and galena that commonly have low pyrite and pyrrhotite contents.

Differences in gold:silver ratios in the district, as compiled from assays of drill-hole samples, ore reserves, and past production, also reflect metal zoning within the Copper Canyon porphyry copper system and its precious metal deposits. The average Au:Ag ratios for the metal zones are: copper-gold-silver zone, 0.066; gold-silver zone, 0.530; and lead-zinc-silver zone, 0.020 (fig. E23). An average Au:Ag ratio for the Copper Canyon stock is 0.057, closely comparable to that for the copper-gold-silver zone situated immediately adjacent to the stock.

The distal Tomboy-Minnie deposits exhibit a zoning of metals similar to that at the proximal deposits of the Copper Canyon system, but the overall gold:silver ratio is higher. Data for the Tomboy-Minnie area were taken from the first assay interval from more than 200 percussion drill holes. Both ore bodies are outlined clearly by the gold:silver ratio in samples from the percussion drill holes (fig. E24). However, Au:Ag ratios ≥1 in assays of drill-hole samples are a better indication of the surface projection of ore than gold assays only of samples from the first interval of percussion holes, as described in Blake and Kretschmer (1983, fig. 5). A final Au:Ag ratio of ≥1 was determined from metal-production data for both deposits which differs somewhat from the announced pre-production ratio determined from percussion drill holes.

These Au:Ag ratios in the Copper Canyon precious and base metal deposits, including the Tomboy-Minnie gold occurrences, compare well with those described by Boyle (1979). He concluded that the Au:Ag ratios for gold-bearing skarn deposits elsewhere are quite varied and can range from 0.005 to 10 (Boyle, 1979, table 43, p. 202). The Au:Ag ratios in the several zones at Copper Canyon are certainly more restricted, ranging from 0.020 to 1, but most importantly, they appear to be characteristic of metal zones recognized earlier in the district.

Metal zoning within the Tomboy-Minnie deposits reflects protracted deposition of gold, zinc, and silver primarily within a favorable stratigraphic unit. This sequence of metal deposition may represent a contact-metasomatic occurrence related to a nearby igneous body separate from the main intrusive mass of the system. The thickest part of the gold zone, shown in figure E22, generally coincides with rocks that have undergone intense retrograde hydrothermal alteration, fracturing, brecciation, and faulting. Although no igneous rocks have been recognized in the Tomboy deposit, a north-striking, silicified granodiorite porphyry dike crops out in the east wall of the pit at the Minnie deposit (fig. E21). This dike contains anomalous gold. The overall zoning pattern and local structural preparation of the rocks in the Tomboy-Minnie deposits suggest that such mineralization could have been related to a heat source somewhere at depth near the granodiorite dike.

STUDIES OF FLUID INCLUSIONS AND STABLE ISOTOPES OF SULFUR

The results of standard fluid-inclusion and sulfur isotope studies of selected samples from the Tomboy gold deposit are included in a report by Theodore and others (1986). A brief summary of some of the more important conclusions of that study is presented here. As we have described, the introduction of gold occurred penecontemporaneously with the replacement of earlier diopside alteration assemblages by actinolite-tremolite- and chlorite-dominant assemblages. Temperatures ranged widely during these changes in silicate mineralogy, decreasing from about 500 °C during the earliest hydrosilicate stages to about 220 °C during the final stages. Preliminary fluid-inclusion studies suggest that $CaCl_2$-rich boiling fluids first circulated there; these were apparently followed by a vapor-dominant stage. Eventually highly saline, late-stage fluids possibly were responsible for much of the introduction of gold. Fluid-inclusion relations in the Tomboy deposit suggest that fluids displaying highly diverse chemistries and wide-ranging temperatures circulated repeatedly through the rocks as the porphyry system centered at Copper Canyon evolved. Apparently some of the earliest epigenetic fluids to circulate through the deposit, fluids that were trapped as secondary fluid inclusions in detrital fragments of quartz in the Battle Formation, were boiling at temperatures in the range of 400 to 500 °C. Apparently they contained appreciable amounts of $CaCl_2$: as much as about 25 weight percent $CaCl_2$-equivalent has been determined by Theodore and others (1986) to occur in some liquid + vapor fluid inclusions. In fact, these fluid inclusions are abundant and relatively large (typically from 15 to 90 μm in largest dimension), and are the predominant fluid-inclusion type in many microdomains studied in the deposit.

The early-stage, $CaCl_2$-dominant fluids apparently were followed by a vapor-dominant, intermediate stage in the range 320–400 °C, wherein the circulating fluids show progressively increasing abundances of dissolved

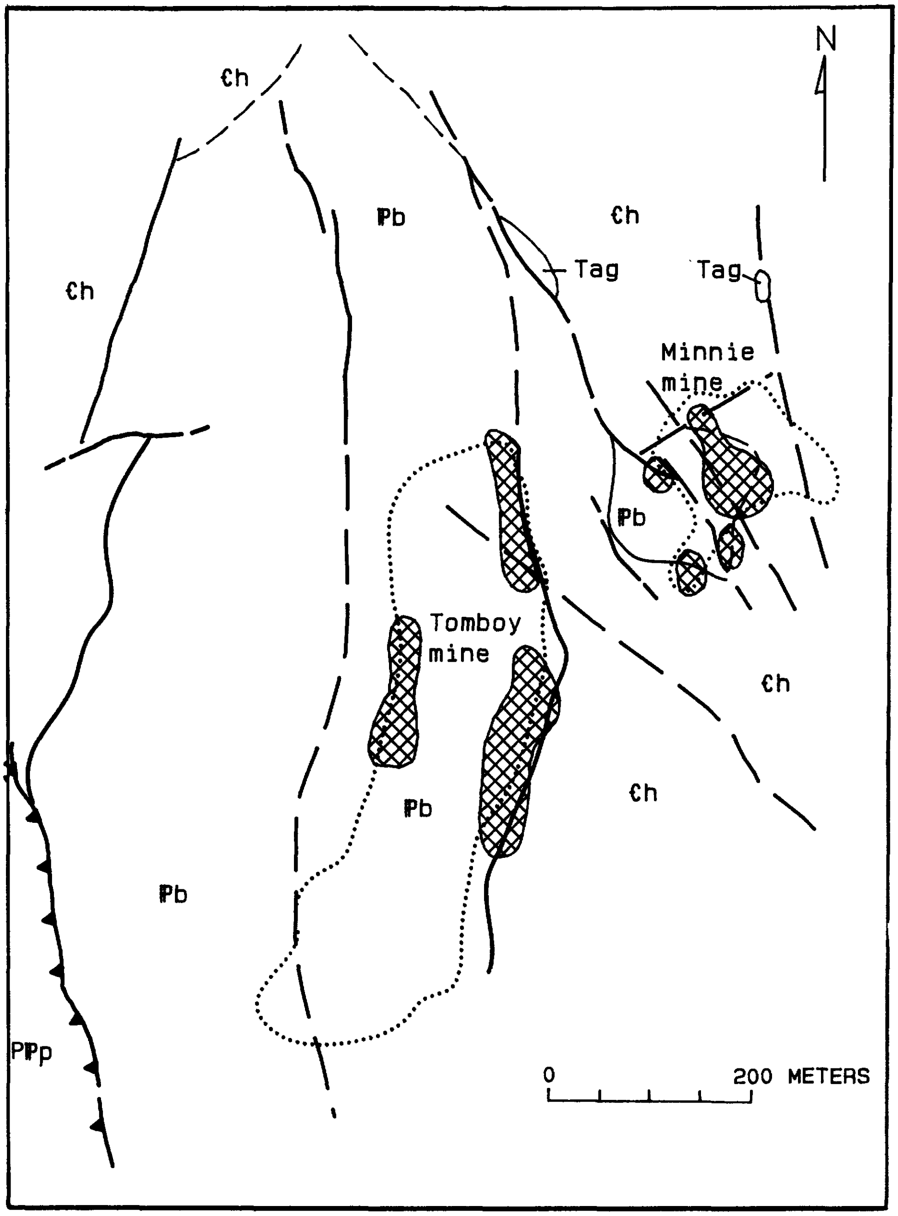


Figure E24. Geologic sketch map of the Tomboy-Minnie deposits showing areas that include Au:Ag ratios ≥ 1 in the first assay interval in percussion drill holes (crosshatched pattern). These data indicate the positions of the ore bodies (dotted outlines). Tag, altered Tertiary granodiorite porphyry of Copper Canyon; IPb, Pennsylvanian Battle Formation; Ꞓh, Cambrian Harmony Formation. Light lines, contacts; dashed where inferred. Heavy lines, faults; dashed where inferred. Sawteeth on upper plate of thrust.

NaCl and KCl. During this stage, the fluids circulating through the deposit also contained minimal amounts of carbon dioxide, as shown by fluid inclusions that contain liquid carbon dioxide at room temperature. The bulk of the actinolite in the deposit probably was deposited during this stage, roughly 320–400 °C.

The fluid-inclusion studies of Theodore and others (1986) reinforce the suggestion that the heat source associated with mineralization at the Tomboy deposit must be closer than the altered granodiorite porphyry of Copper Canyon that crops out almost 1 km to the north-northwest. An apophysis of altered granodiorite porphyry may occur at depth somewhere in the general area of the Tomboy-Minnie deposits. Further, the relation of fluids boiling at times in the range 400–550 °C at the Tomboy and fluids boiling at approximately 350–375 °C during the ore-forming stage(s) at the East ore body described by Nash and Theodore (1971), together with the fact that both ore bodies are approximately the same elevation and occur in the same tectonic block, suggests that the interface between boiling and nonboiling fluids during the early stages of mineralization at the Tomboy must have been at a significant depth below the deposit. This depth may have been as much as 2.2 km below the paleosurface based on preliminary calculations that use 450 °C as a representative temperature for boiling, mostly $CaCl_2$-bearing, aqueous solutions. Indeed, the model for porphyry systems such as this probably should include a gradational interface between boiling fluids above and nonboiling fluids below that drapes umbrellalike across the system; the interface might have deep lobate extensions, possibly controlled by premineral faults, near the gold-enriched margins of the system.

The sulfur isotopic compositions of 35 sulfide mineral separates from the Copper Canyon deposits, 10 from the West ore body, 9 from the East ore body, and 16 from the Tomboy ore body, were measured by Theodore and others (1986) in order to constrain the source(s) of sulfur in the deposits and possibly on the temperature of mineralization. The $\delta^{34}S$ values for all sulfide minerals range from +1.1 to +5.3 per mil, except for a galena sample from the Tomboy ore body with a very depleted value of –5.2 per mil. Neglecting this galena sample, the average $\delta^{34}S$ values of the sulfide minerals from the East and Tomboy ore bodies are within 0.5 per mil of each other and are about 2 per mil heavier than the average value for the sulfide minerals from the West ore body. The East and Tomboy deposits are certainly at more distal portions of the system than the West ore body, and they may contain a larger component of heavy sulfur derived from syngenetic-diagenetic sulfur in sedimentary rocks and (or) pre-Tertiary evaporite or sulfate deposits. Pyrite enriched in $\delta^{34}S$ from the Roberts Mountains Formation and bedded barite of Devonian age as heavy as +56 per mil are known from central Nevada (Rye and Ohmoto, 1974; Rye and others, 1978). Still, the narrow range of $\delta^{34}S$ values for the East and Tomboy ore bodies suggests that the contribution of heavy, crustal sulfur was relatively small and highly homogenized. Dissolution and reprecipitation of preexisting sulfides and sulfates do not appear to have been an important process in the formation of the Copper Canyon deposits. These data suggest that sulfur mostly from a magmatic or deep-crustal source was carried by hydrothermal fluids as aqueous H_2S to the West, East, and Tomboy deposits.

CONCLUSIONS

Copper skarn ores in many porphyry systems may contain unrecognized high gold–low copper zones that may have been overlooked previously because of their high contents of seemingly barren pyrrhotite and pyrite. Gold mineralized rock at the Tomboy-Minnie deposits formed as a result of introduction of large amounts of iron sulfide minerals, mostly pyrrhotite and pyrite, together with gold during retrograde, hydrosilicate-sulfide stages marginal to copper-bearing skarn. The introduction of gold occurred penecontemporaneously with the replacement of early diopside alteration assemblages by actinolite-tremolite- and chlorite-dominant assemblages. Temperatures of deposition ranged widely, decreasing from about 500 °C during the earliest phases of the hydrosilicate stages to about 220 °C during the final stages. Probably the gold-rich ore at the Tomboy-Minnie deposits formed at about the same time as the copper-gold-silver ores in the East ore body; an actinolite-tremolite assemblage also is a common accessory silicate assemblage in the East ore body. All these deposits at Copper Canyon bear many similarities to porphyry-related copper skarns elsewhere (Einaudi and others, 1981). However, the porphyry copper system at Copper Canyon belongs to a "wallrock" end-member of this deposit type, wherein all the ore occurs in the country rock surrounding a genetically associated intrusive body (Titley, 1972).

The Tomboy-Minnie deposits are included by Orris and others (1987) with their gold-skarn class of deposits. Relative to 31 gold skarns worldwide, the ores at the Tomboy-Minnie are significantly greater than the median tonnage (400,000 t) and somewhat less than the median grade (3.54 g/t versus 5.0 g/t).

Many porphyry copper systems that include considerable "wallrock" components historically have yielded significant amounts of gold. For example, production of gold between 1904 and 1972 for the Bingham, Utah, deposits has amounted to approximately 8 million oz (Gilmour, 1982). The grade of gold at Bingham up to 1972 was 0.0064 oz Au/ton in the disseminated copper zone (Gilmour, 1982), whereas the grade in some of the copper skarns there (Highland Boy Mine) was about 0.07 oz Au/ton (Einaudi, 1982). The Ely, Nev. deposit produced about 3 million oz of gold (D.P. Cox and D.A. Singer, unpub. data, 1984). The system at Copper Canyon contained a minimum of about 3.3 million oz gold initially. However, the overall grade of gold at Copper Canyon was about 0.025 oz Au/ton, and that of the gold-silver zone deposits was about 0.1–0.15 oz Au/ton—and locally in excess of these values (Wotruba and others, 1986).

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