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).

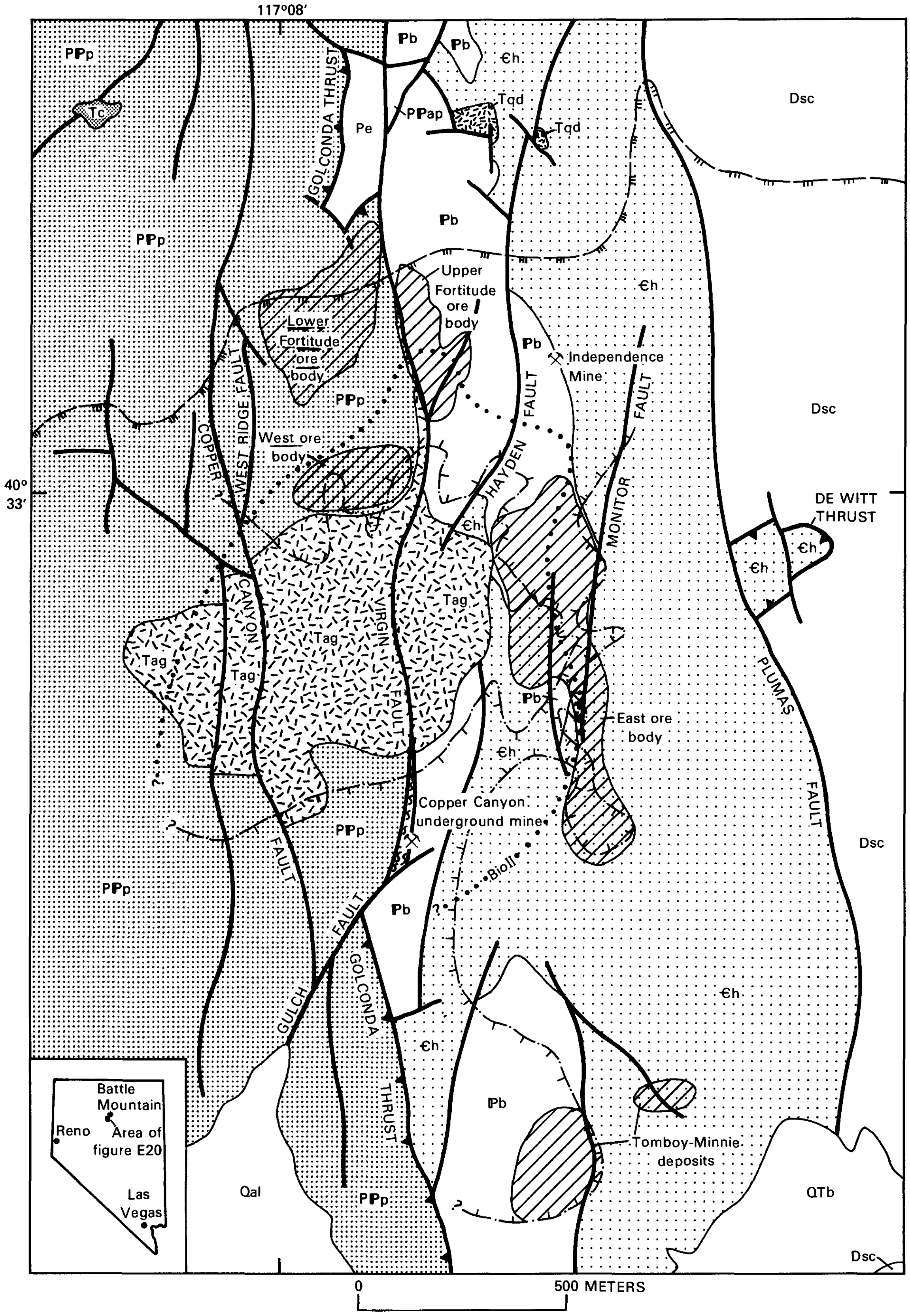
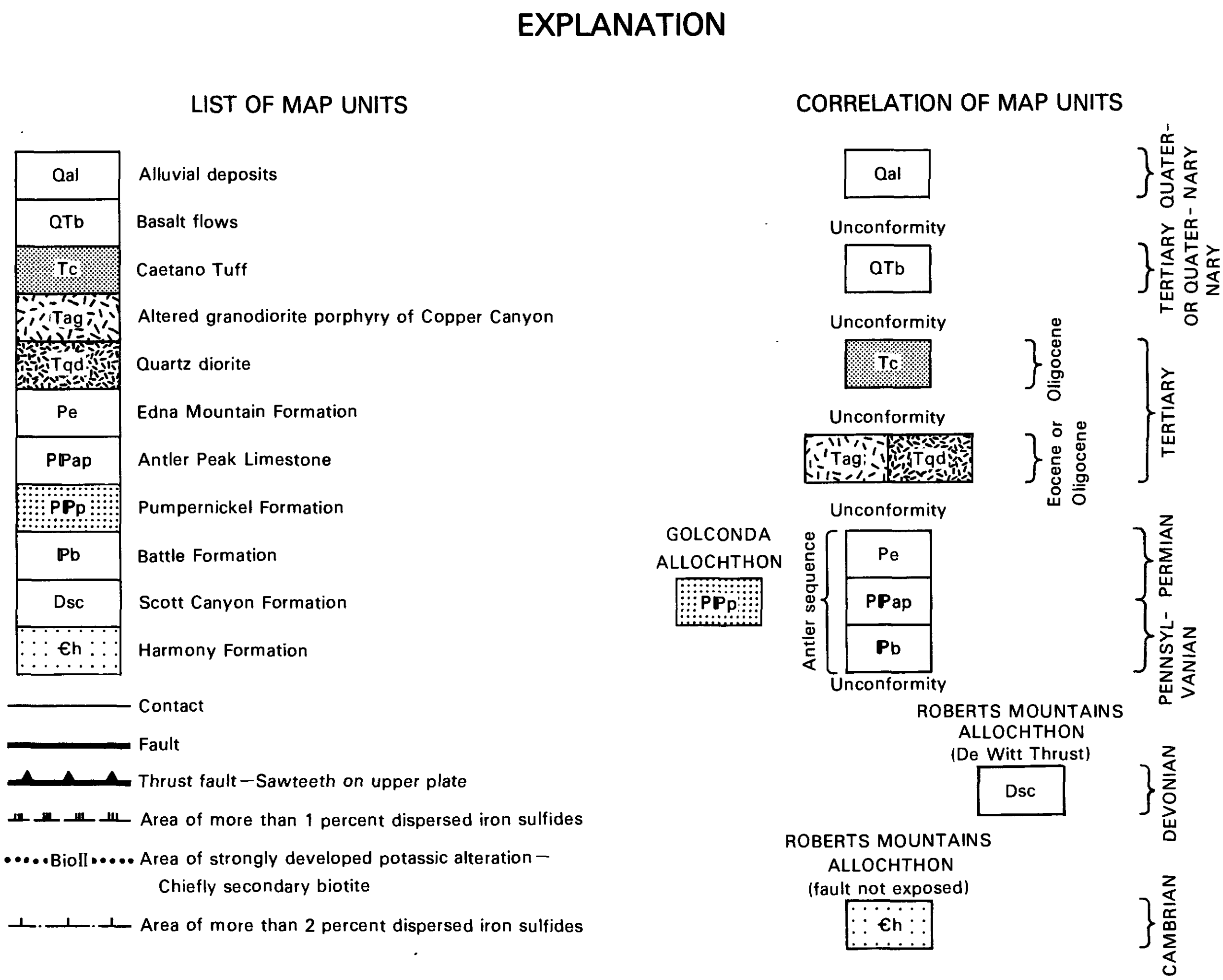


Figure E20 (above and facing page). Geologic sketch map of Copper Canyon area, Lander County, Nevada.



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.

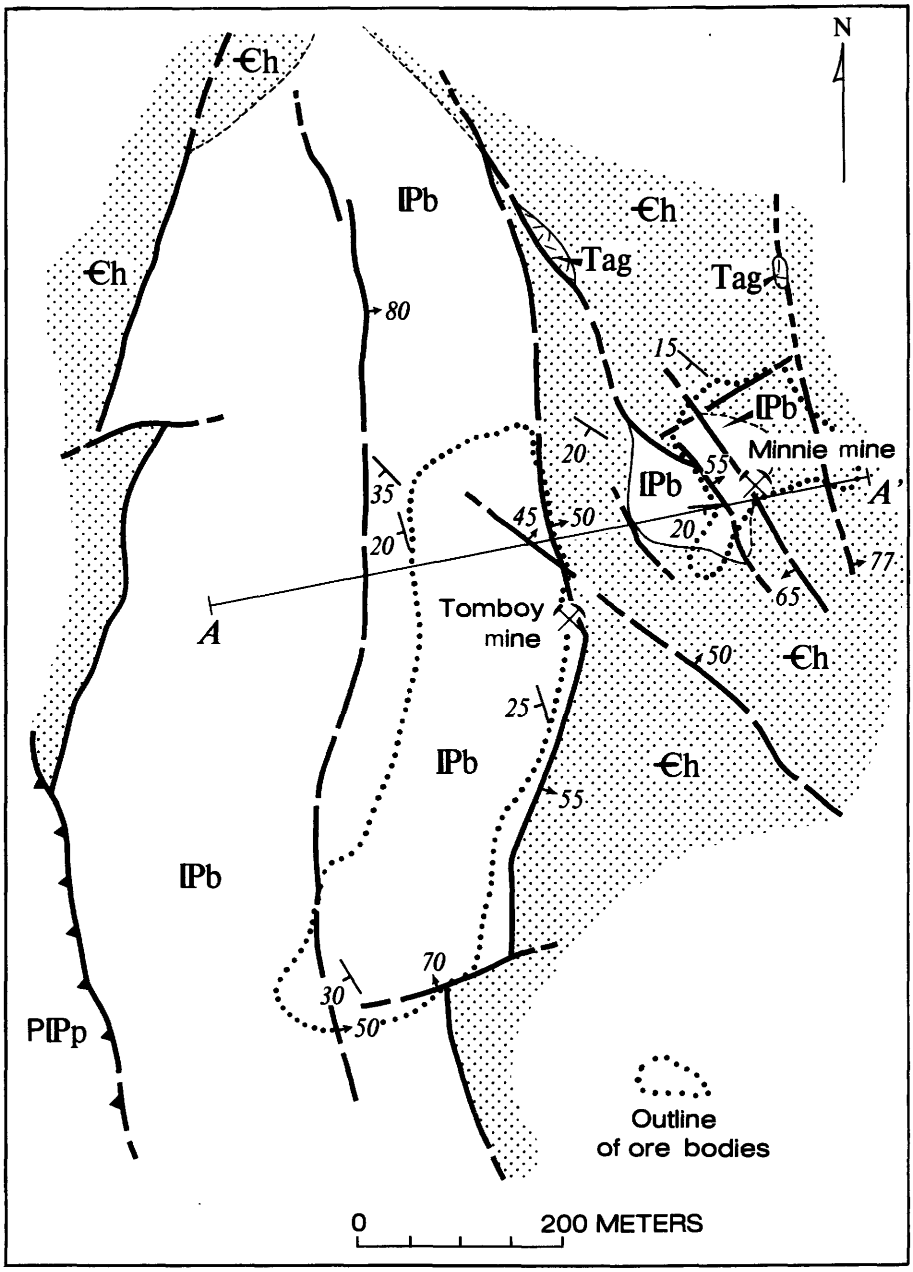
During late Eocene or early Oligocene time the porphyritic granodiorite stock intruded the sequence of Paleozoic sedimentary and volcanic rocks at Copper Canyon. The stock contains phenocrysts of quartz, plagioclase, potassium feldspar, and biotite set in a mosaic, microaplitic groundmass of quartz, 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



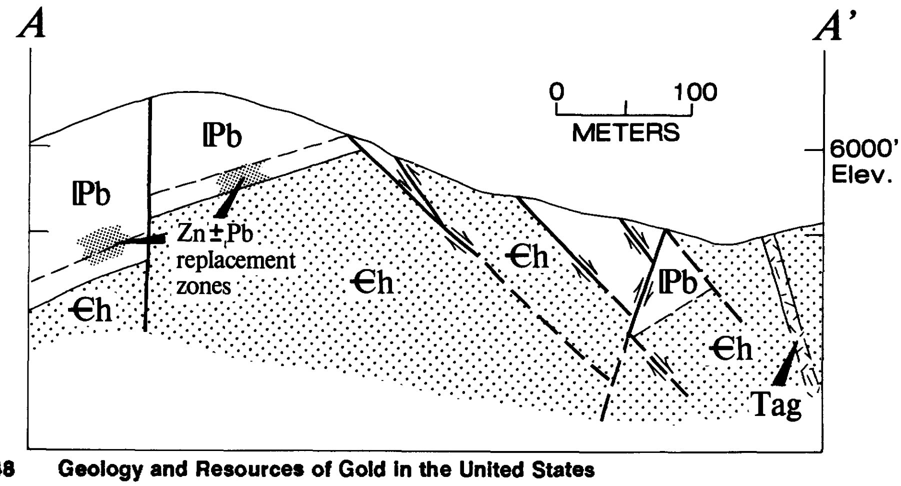


Figure E21. Generalized geologic map and cross section *A–A'* of Tomboy-Minnie area, Lander County, Nevada. Tag, altered granodiorite of Copper Canyon; PIPp, Permian-Pennsylvanian Pumpernickel Formation; IPb, Pennsylvanian Battle Formation; €h, Cambrian Harmony Formation. Heavy lines, faults; dashed 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.

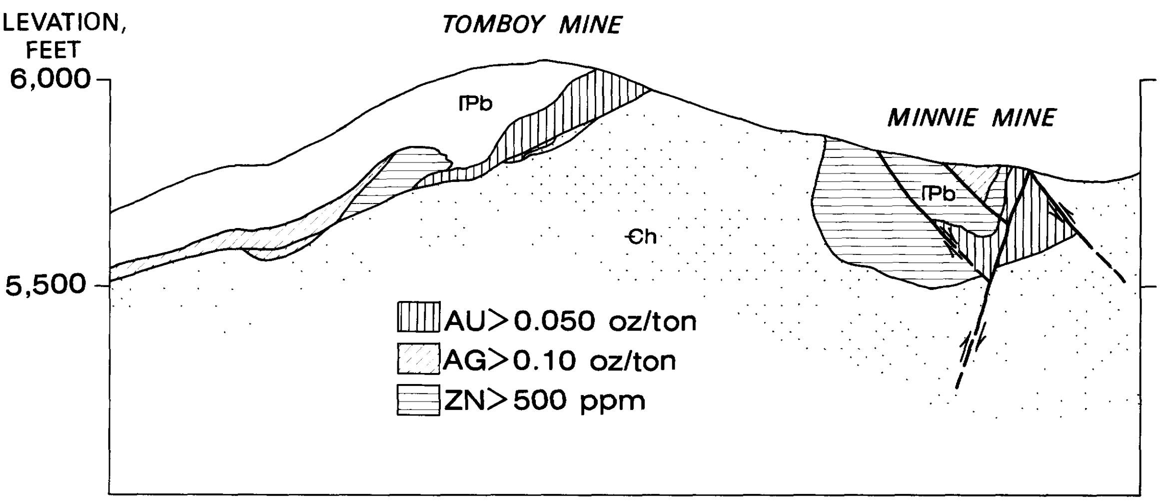


Figure E22. Idealized northeast-trending cross section through the Tomboy-Minnie deposits showing rocks containing >0.05 oz Au/ton, >0.10 oz Ag/ton, and >500 ppm Zn. Data taken from 19 percussion drill holes along the trace of the cross section. IPb, Pennsylvanian Battle Formation; Ꞓh, Cambrian Harmony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

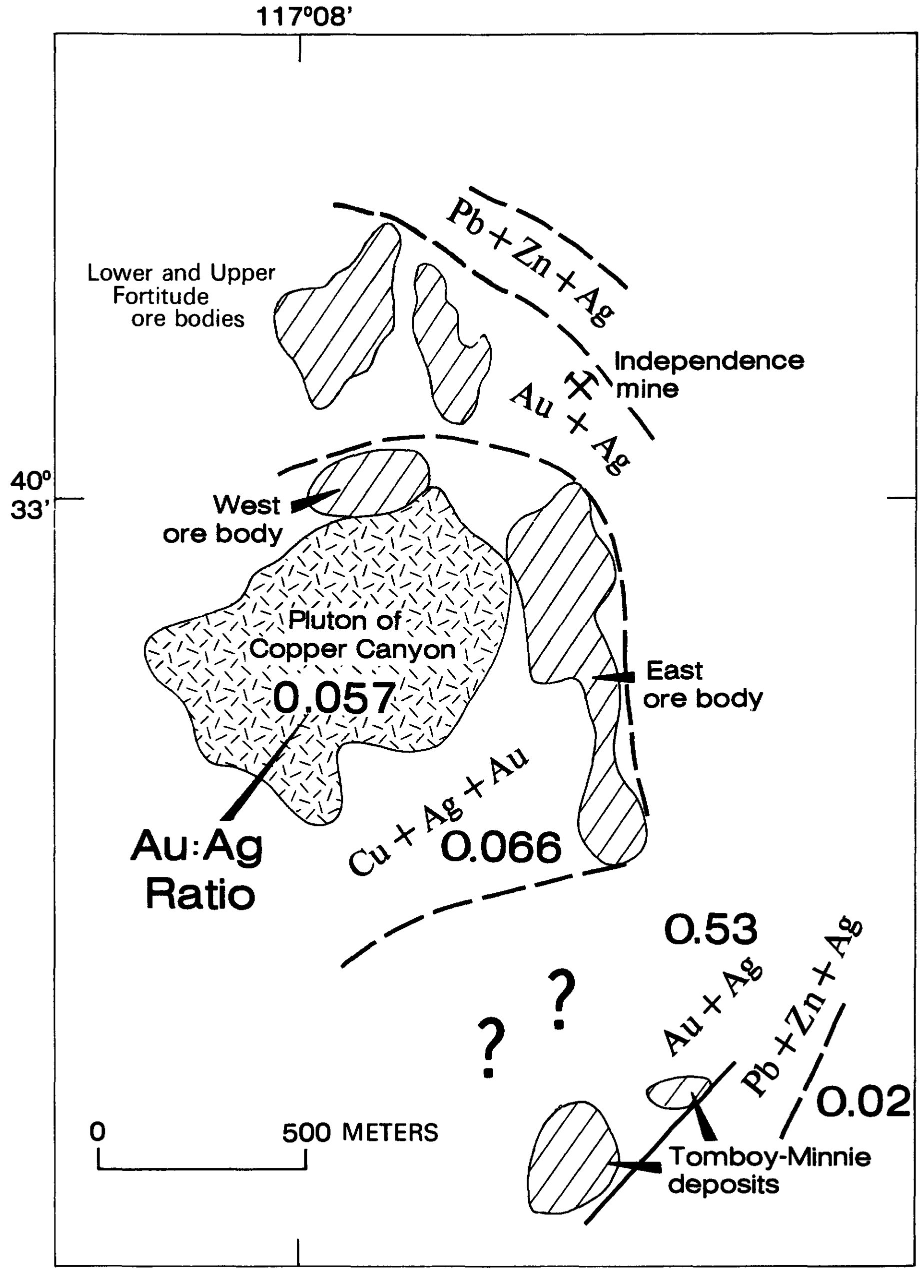


Figure E23. Zonal distribution of metals and Au:Ag ratios in the Copper Canyon area.

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

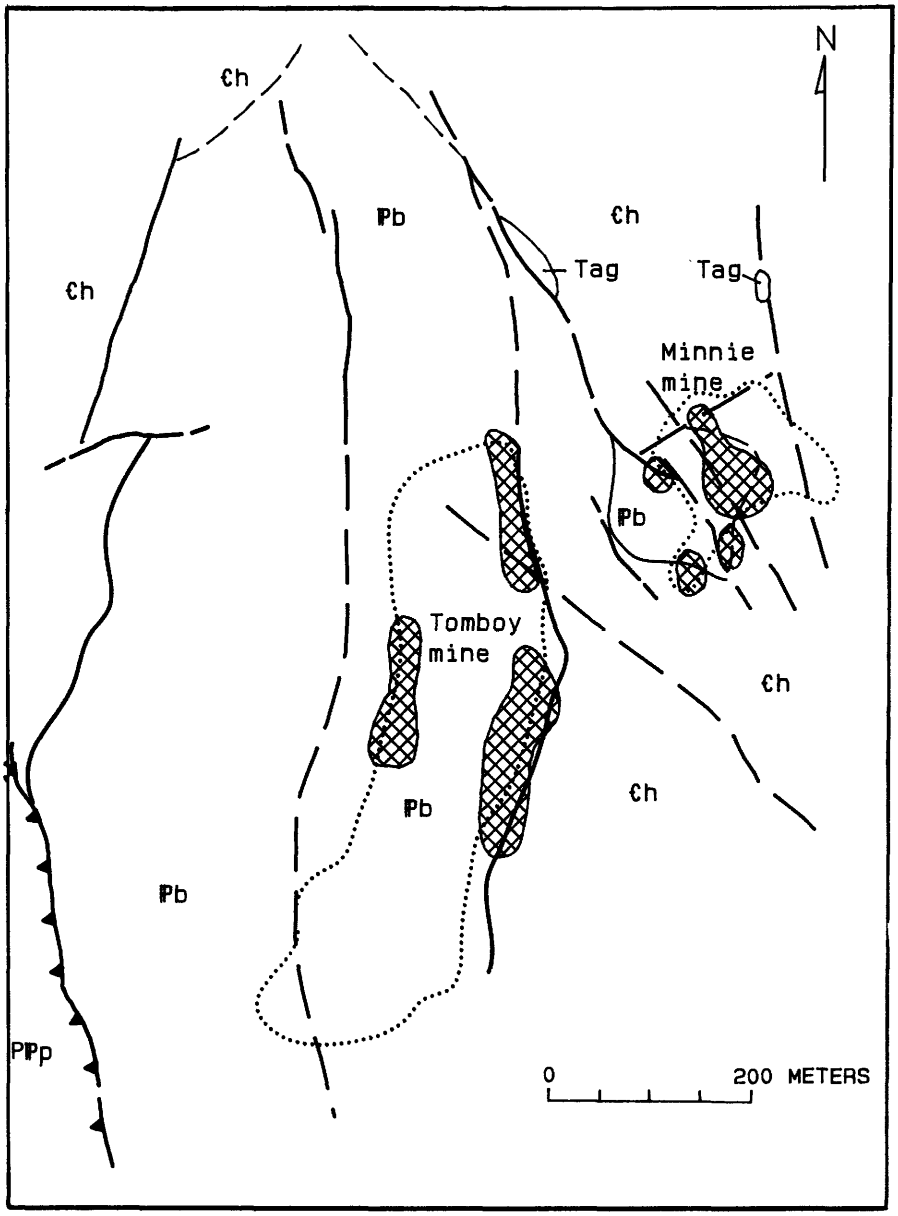


Figure E24. Geologic sketch map of the Tomboy-Minnie deposits showing areas that include Au:Ag ratios ≥ 1 in the first assay interval in percussion drill holes (crosshatched pattern). These data indicate the positions of the ore bodies (dotted outlines). Tag, altered Tertiary granodiorite porphyry of Copper Canyon; ⲢPb, 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).

Manuscript received by scientific editors May 1984

REFERENCES CITED

Anonymous, 1981, Major discoveries promise big surge in U.S. gold production: Arizona Paydirt, November, 1981, p. 12.

Anonymous, 1986, New development highlights—Nevada: Engineering and Mining Journal International Directory, Mining Activity Digest, v. 13, no. 5, October 24, 1986, p. 12.

Anonymous, 1987, Battle Mountain Gold reports on projects: California Mining Journal, January 1987, v. 56, no. 5, p. 29–30.

Argall, G.O., Jr., 1986, The golden glow at Battle Mountain: Engineering and Mining Journal, February, 1986, p. 32–37.

Bateman, P.C., 1961, Granitic formations in the east-central Sierra Nevada near Bishop, California: Geological Society of America Bulletin, v. 22, p. 1521–1537.

Blake, D.W., and Kretschmer, E.L., 1983, Gold deposits at Copper Canyon, Lander County, Nevada: Nevada Bureau of Mines and Geology Report 36, p. 3–10.

Blake, D.W., Theodore, T.G., and Kretschmer, E.L., 1978, Alteration and distribution of sulfide mineralization at Copper Canyon, Lander County, Nevada: Arizona Geological Society Digest XI, p. 67–78.

Boyle, R.W., 1979, The geochemistry of gold and its deposits: Geological Survey of Canada Bulletin 280, 584 p.

Einaudi, M.T., 1982, Description of skarns associated with porphyry copper plutons, southwestern North America, *in* Titley, S.R., ed., Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, Ariz., The University of Arizona Press, p. 134–183.

Einaudi, M.T., Meinert, L.D., and Newberry, R.J., 1981, Skarn deposits, *in* Skinner, B.J., ed., Seventy-fifth anniversary volume, 1905–1980, Economic geology: New Haven, Conn., The Economic Geology Publishing Company, p. 317–391.

Epler, Bill, 1985, Battle Mountain Gold gains listing on Toronto stock exchange: Paydirt, December 1985, p. 10B–11B.

Gilmour, Paul, 1982, Grades and tonnages of porphyry copper deposits, *in* Titley, S.R., ed., Advances in geology of the porphyry copper deposits: Tucson, Ariz., The University of Arizona Press, p. 7–35.

Jackson, Dan, 1982, How Duval transformed its Battle Mountain properties from copper to gold production: Engineering and Mining Journal, v. 183, no. 10, p. 95, 97, 99.

Johnson, M.G., 1973, Placer gold deposits of Nevada: U.S. Geological Survey Bulletin 1356, 118 p.

Lockard, D.W., and Schilling, J.H., 1983, The mineral industry of Nevada, *in* Minerals Yearbook, Centennial Edition 1981: U.S. Bureau of Mines, v. II, Area Reports, p. 319–330.

Lucas, J.M., 1982, Gold, *in* Minerals Yearbook, Centennial Edition 1981: U.S. Bureau of Mines, v. I, Metals and Minerals, p. 365–392.

Nash, J.T., and Theodore, T.G., 1971, Ore fluids in the porphyry copper deposit at Copper Canyon, Nevada: Economic Geology, v. 66, p. 385–399.

Orris, G.J., Bliss, J.D., Hammarstrom, J.M., and Theodore, T.G., 1987, Descriptions and grades and tonnages for gold-bearing skarns: U.S. Geological Survey Open-File Report 87–273, 50 p.

Roberts, R.J., 1964, Stratigraphy and structure of the Antler Peak quadrangle, Humboldt and Lander Counties, Nevada: U.S. Geological Survey Professional Paper 459–A, 93 p.

Roberts, R.J., and Arnold, D.C., 1965, Ore deposits of the Antler Peak quadrangle, Humboldt and Lander Counties, Nevada: U.S. Geological Survey Professional Paper 459–B, 94 p.

Rye, R.O., and Ohmoto, Hiroshi, 1974, Sulfur and carbon isotopes and ore genesis—A review: Economic Geology, v. 69, p. 826–842.

Rye, R.O., Shawe, D.R., and Poole, F.G., 1978, Stable isotope studies of bedded barite at East Northumberland Canyon in Toquima Range, Central Nevada: U.S. Geological Survey Journal of Research, v. 6, p. 221–229.

Sayers, R.W., Tippett, M.C., and Fields, E.D., 1968, Duval's new copper mines show complex geologic history: Mining Engineering, v. 20, no. 3, p. 55–62.

Silberling, N.J., and Roberts, R.J., 1962, Pre-Tertiary stratigraphy and structure of northwestern Nevada: Geological Society of America Special Paper 72, 58 p.

Sillitoe, R.H., 1983, Styles of low grade gold mineralization in volcano-plutonic arcs: Nevada Bureau of Mines and Geology Report 36, p. 52–68.

Speed, R.C., 1977, Island-arc and other paleogeographic terranes of late Paleozoic age in the western Great Basin, *in* Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, Los Angeles, p. 349–362.

Theodore, T.G., and Blake, D.W., 1975, Geology and geochemistry of the Copper Canyon porphyry copper deposit and surrounding area, Lander County, Nevada: U.S. Geological Survey Professional Paper 798–B, 86 p.

——— 1978, Geology and geochemistry of the West orebody and associated skarns, Copper Canyon porphyry copper deposits, Lander County, Nevada, *with a section on* Electron microprobe analyses of andradite and diopside, by N.G. Banks: U.S. Geological Survey Professional Paper 798–C, 85 p.

Theodore, T.G., Howe, S.S., Blake, D.W., and Wotruba, P.R., 1986, Geochemical and fluid zonation in the skarn environment at the Tomboy-Minnie gold deposits, Lander County, Nevada: Journal of Geochemical Exploration, v. 25, p. 99–128.

Theodore, T.G., Silberman, M.L., and Blake, D.W., 1973, Geochemistry and K-Ar ages of plutonic rocks in the Battle Mountain mining district, Lander County, Nevada: U.S. Geological Survey Professional Paper 798–A, 24 p.

Titley, S.R., 1972, Intrusion, and wall rock, porphyry copper deposits: Economic Geology, v. 67, p. 122–124.

Wotruba, P.R., Benson, R.G., and Schmidt, K.W., 1986, Battle Mountain describes the geology of its Fortitude gold-silver deposit at Copper Canyon: Mining Engineering, July 1986, p. 495–499.

☆U.S. GOVERNMENT PRINTING OFFICE: 1990-773-047/06061