LOW SULFIDE AU QUARTZ VEINS
(MODEL 36a; Berger, 1986)

by Richard J. Goldfarb, Byron R. Berger, Terry L. Klein, William J. Pickthorn, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of Archean through Tertiary quartz veins, primarily mined for their gold content, that generally contain no more than 2 to 3 volume percent sulfide minerals, mainly pyrite, in allochthonous terranes dominated by greenstone and turbidite sequences that have been metamorphosed to greenschist facies. Wall rocks contain abundant carbonate and sulfide minerals, quartz, and sericite. Arsenic and antimony are enriched in alteration haloes (fig. 1). These deposits are also known as mesothermal, Mother Lode-type, orogenic, metamorphic rock-hosted, greenstone gold (Archean), turbidite-hosted (Phanerozoic), and slate belt gold (Phanerozoic) deposits.

Low sulfide gold quartz veins in the United States are presently being mined and prospected within rocks of accreted lithotectonic terranes along both continental margins. Development of Paleozoic lode deposits in recent years has been restricted to the South Carolina part of the Carolina slate belt. Open pit mining of the more than 1.5 million oz of gold at the Ridgeway mine, the largest of the deposits, is continuing at a rate of about 100,000 oz/yr. In the Mother Lode region of central California, a few old mines have been reopened in the last 10 to 15 years as open pit operations. Each has been recovering 500,000 to 750,000 oz of gold from low-grade, Early Cretaceous deposits. Production from the Alaska-Juneau and Kensington Eocene vein deposits in southeastern Alaska by underground operations is scheduled to commence during the next few years and will yield about 6 million oz of gold. In the Alaskan interior, open-pit mining will eventually yield 4 million oz of gold from the mid-Cretaceous Fort Knox deposit.

Examples

Yilgarn Block, Western Australia; Abitibi Belt, Superior Province, Canada; Yellowknife, Northwest Territory, Canada; Bendigo/Ballarat, Victoria, Australia; Murantau, Uzbekistan; Mother Lode, Calif.; Juneau Gold Belt, Alaska; Otago Schist Belt, South Island, New Zealand.

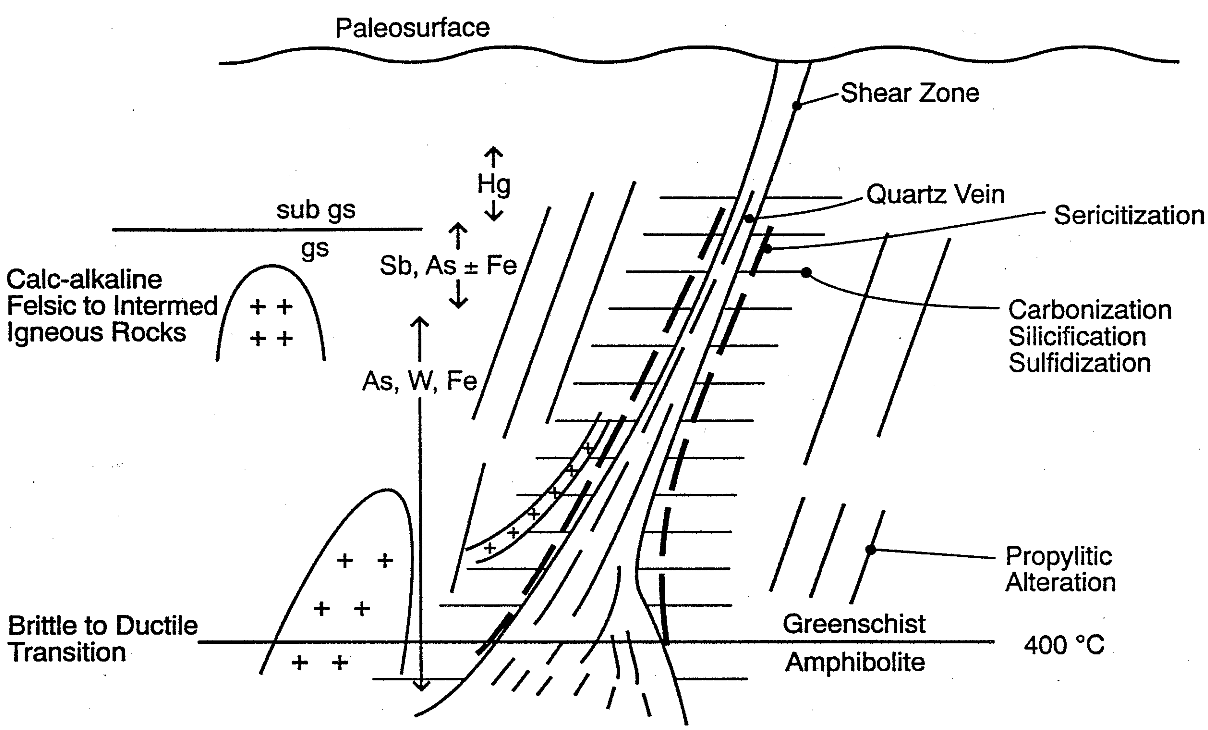

Figure 1. Schematic geologic cross section of a low-sulfide gold deposit.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) may include silica-carbonate mercury (Model 27c), and gold-antimony (Model 36c), which may reflect shallower exposures of similar hydrothermal systems in areas of limited erosion. In areas of extensive uplift and erosion, gold lodes are reconcentrated in extensive placer accumulations (Model 39a). Low sulfide gold quartz vein deposits subjected to tropical weathering can produce lateritic saprolite (eluvial placer) deposits (Model 38g; McKelvey, 1992). Much older, pre-accretionary Cyprus, Besshi, and Kuroko volcanogenic massive sulfide deposits (Models 24a, 24b, 28a) are spatially associated with gold veins in terranes that contain significant volumes of volcanic rock.

Potential environmental considerations

(1) Moderate amounts of acid mine drainage may be present where local, relatively high sulfide mineral concentrations are present in gold ore, where broad zones of sulfidization characterize wall rocks, and (or) where much of the ore is hosted by greenstone that has relatively low acid-buffering capacity.
(2) Oxidation of mine tailings that contain sulfide minerals, particularly arsenopyrite, or soil formed from unmined, yet sulfide-mineral-bearing rock can release potentially hazardous arsenate, arsenite, and methylarsenic species.
(3) Increased concentrations of arsenic, antimony, and other trace metals may be present downstream from deposits. Cyanide used for gold extraction at many active mines is a potential additional contaminant in waste water discharge.
(4) Mercury amalgamation carried out during historic operations may be a source of mercury contamination in aquatic life and in surface sediment. Continued use of mercury amalgamation and roasting for gold extraction in some parts of the world is a direct and very serious health hazard.
(5) Disposal of tailings from developed deposits can cause sedimentation problems in adjacent waterways.
(6) Modern open-pit mining methods, allowing for development of previously uneconomic, low-grade gold deposits pose quality-of-life concerns. Potential concerns include mining-related visual impacts, increased traffic and noise, and dust generation. Open-pit mining also produces significantly greater volumes of untreated waste rock.
(7) Long term exposure to arsenic concentrated in tailings can cause cancer and kidney disease.

Exploration geophysics

Silicified rock, much of which corresponds to wall rock that contains abundant sulfide minerals, is commonly associated with local resistivity highs. Silicified rock and carbonate minerals along veins increase density and resistivity and may allow indirect sulfide mineral identification using detailed electromagnetic, direct current resistivity, and micro-gravity mapping. Disseminated pyrite, arsenopyrite, and chalcopyrite distributions can be outlined using induced polarization/resistivity surveys. Piezo-electricity may locate sulfide-mineral-bearing quartz veins. Host rocks that contain at least moderate amounts of magnetite may have associated magnetic lows due to magnetite destruction in alteration-halos.

References

Geology: Berger (1986), Bliss (1986, 1992), Groves and others (1989), Kerrich and Wyman (1990), Kontak and others (1990), Nesbitt (1991), Berger (1993), Goldfarb and others (1993), Phillips and Powell (1993), and Klein and Day (1994).
Environmental geology and geochemistry: Bowell and others (1994), Callahan and others (1994), Cieutat and others (1994), Azcue and others (1995), and Trainor and others (in press).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposit size is extremely variable. Archean deposits-mean tonnage is 1.08 million metric tonnes; range is 0.004 to 199 million metric tonnes. The mean tonnage of Phanerozoic deposits is 0.03 million metric tonnes; range is 0.001 to 25 million metric tonnes. The mean tonnage of Chugach-type Phanerozoic deposits is 0.003 million metric tonnes; range is 0.001 to 0.07 million metric tonnes. Because of the high-grade nature of some veins (greater than 30 to 50 g gold/t), many low tonnage deposits (for instance, Chugach-type low sulfide gold deposits; Bliss, 1992) are developed by small, underground workings. Deposits that contain at least 0.5 to 5 million oz gold in low grade ore (generally 2 to 10 g gold/t) have been mined in large, more modern open-pit operations. The largest example of such a deposit is Murantau, Uzbekistan, which contains greater than 140 million oz gold (Berger and others, 1994).

Host rocks

Archean ore is largely hosted by metamorphosed basalt (greenstone), although ultramafic volcanic rocks (komatiite), felsic volcanic rocks, and granitoid intrusions are locally important hosts. Most of these deposits are in preserved cratonic blocks. Phanerozoic deposits are hosted in slate and graywacke in deformed, continental margin orogenic belts. Where competent, pre-ore igneous bodies are present in metasedimentary sequences, they commonly preferentially host vein-bearing fracture systems.

Surrounding geologic terrane

Deposits are restricted to medium-grade, generally greenschist facies, metamorphic rocks. High-tonnage deposits, exemplified by Murantau, Uzbekistan, have a spatial association with major structural zones that are commonly believed to be old terrane boundaries. Contemporaneous calc-alkaline dioritic to granitic plutons, sills, and batholiths within a few tens of kilometers of ore indicate that both are products of regional, middle to lower crustal thermal events.

Wall-rock alteration

Mineral phases vary with host rock lithology; halo width varies with size of hydrothermal system. Alteration zones are poorly developed in metasedimentary host rocks, but are broad and distinct in both felsic and mafic igneous rocks. Silicified rock and carbonate minerals are ubiquitous. Disseminated pyrite and (or) arsenopyrite consistently are present in these broad haloes. Sericite is common, but only close to discrete gold-bearing veins; in some systems, biotite is also present adjacent to veins. Sericite gives way to a chlorite-epidote propylitic zone distal to veins. Talc, chlorite, and fuchsite are also common in alteration zones within ultramafic host rocks; albite is common in granitoid host rocks. Wall rocks are notably enriched in H_2O, CO_2, S, K, Au, W, Sb, and As (Nesbitt, 1991).

Nature of ore

Ore may be present in quartz veins and (or) adjacent sulfidized wall rock. Gold is present as free grains in quartz, as blebs attached to wall rock ribbons, and in veinlets cutting sulfide grains. Individual veins are 1 to 10-m-wide discrete fissure fillings that have strike lengths of less than 100 m. Many veins show ribbon texture or, less commonly, contain brecciated wall rock fragments. In some deposits, ore forms dense stockworks of cm-wide veinlets. Vein swarms at the large deposits can attain 5-km strike lengths, 500 m widths, and extend 2 km down dip. Carbonate minerals may form either (1) restricted alteration zones that range from a few to tens of meters away from small shear zones or (2) may be abundant in rocks within several kilometers of major faults.

Deposit trace element geochemistry

Abundances of silver, arsenic, gold, and iron are consistently anomalous; tungsten and antimony abundances are much less consistently anomalous; bismuth, copper, mercury, lead, and zinc abundances are anomalous in many deposits; less commonly, anomalous amounts of tellurium and molybdenum are detected.

Ore and gangue mineralogy and zonation

(1) Gold is present as native gold and electrum.
(2) Potentially acid-generating sulfide minerals (in order of abundance) are pyrite, arsenopyrite > stibnite > chalcopyrite, pyrrhotite, galena, sphalerite > telluride minerals, tetrahedrite > bismuthinite > molybdenite.
(3) Scheelite and graphite are common.
(4) Potentially acid-buffering carbonate minerals include siderite, ankerite, calcite, magnesite, or ferroan dolomite; the composition of the carbonate species is a function of wall rock chemistry.
(5) Silicate gangue minerals include quartz, muscovite, chlorite, biotite, fuchsite, tourmaline, rutile, albite, and (or) talc.
(6) Zoning is uncommon; mineral assemblages and proportions are commonly consistent over depths of greater than 1,000 m. In some systems, shallow levels may contain more abundant stibnite or sulfosalt minerals and native silver (Berger, 1993). Deeper zones may be more pyrrhotite-rich.

Mineral characteristics

Sulfide minerals are usually present as finely disseminated grains in quartz and wall rocks. In some deposits, massive clots of arsenopyrite, as large as tens of cm, may be present locally. In rare examples, gold-bearing veins may contain massive stibnite (10 to 50 volume percent of the vein material) throughout the deposit (see Berger, 1993).

Secondary mineralogy
Secondary minerals are not common. Occasionally, some arsenopyrite has weathered to scorodite. Minor limonite is present in many veins.

Topography, physiography
The deposits do not form distinct topographic features although in some mining districts (for example, Bendigo, Australia) mineralized zones may form distinctive linear ridges. They may have been emplaced along steep and rapidly uplifting mountain belts; many pre-Tertiary low-sulfide gold-quartz veins are present in more tectonically stable zones of moderate relief.

Hydrology
Veins are generally hosted in permeable fracture zones and hence are also significant local ground water conduits. Mining relatively sulfide-mineral-rich veins of this deposit type could cause discharge of minor volumes of relatively metal-rich ground water. However, seepage from poorly consolidated tailings piles and adits at historic workings is likely to be the most common source of metal contamination of surface water near this type of gold deposit.

Mining and milling methods
Both underground and open pit mining methods are presently being used to extract ore. In the United States, except for southeastern Alaska, open pit mining is most common. During milling, ore is usually crushed and ground in a ball mill; subsequently, gravity concentration is used to remove the largest gold particles. Remaining ore is reground, classified and thickened, recycled through the gravity concentrator, and then processed in cyanide vats for 48 hours. The slurry is subsequently sent to a carbon-in-pulp circuit where dissolved gold is adsorbed on carbon. Gold is then stripped from carbon and electroplated on steel wool before being refined into bullion in a furnace. Alternatives to vat leaching during cyanidation include *in situ* and heap leaching.

In some parts of the world, mercury amalgamation is still being used to aid gold recovery. Sulfur compounds, which adversely impact the amalgamation process, are eliminated by first roasting ore. Mixing mercury with gold concentrates results in amalgam that leaves gold behind when the mercury is volatilized.

ENVIRONMENTAL SIGNATURES
Drainage signatures
For both mined and unmined orebodies, low sulfide mineral contents of ore and acid-buffering capacity of widespread carbonate alteration assemblages generally prevent significant acid-mine drainage and heavy metal contamination associated with this deposit type.
Natural drainage: Limited data (Carrick and Maurer, 1994; Cieutat and others, 1994; Trainor and others, in press) suggest that unmined occurrences have little impact on surface water pH or trace element content. In southern Alaska, data indicate that arsenic abundances increase from <5 to 6 µg/l, iron from <20 to 140 µg/l, and sulfate from <2 to 3 to 5 mg/l where natural water encounters unmined low-sulfide gold quartz vein occurrences.
Mine drainage: Arsenic and iron abundances in water draining small workings may be enhanced by one to two orders-of-magnitude relative to background abundances downstream from unmined occurrences (Cieutat and others, 1994; Trainor and others, in press). Other metals do not exhibit corresponding enrichments. Even water draining directly from major pits and extensive underground workings can have neutral pH and low metal contents; water draining the Alaska-Juneau pit and underground workings, Alaska's largest gold mine, contain <6 µg/l arsenic and <100 µg/l iron at a pH of 8.0; sulfate abundances in this water are as much as 340 mg/l (Echo Bay Mines, unpub. company data). Water flowing out the portal of the Independence, Alaska, mine in the Willow Creek district, the fourth largest past lode gold producer in the state, has a pH of 7.8 and contains <40 µg/l iron, 37 µg/l arsenic, and <4 µg/l cadmium, copper, lead, antimony, tungsten, and zinc (R.J. Goldfard, unpub. data, 1995).

In rare examples, locally high concentrations of sulfide minerals can lead to significant metal-rich and (or) acid mine drainage. Contaminated water that drained from an old adit at the site of an open pit gold mine at Macraes Flat, South Island, New Zealand, which had a pH of 2.9 and elevated dissolved metal abundances, including as much as 77 mg/l zinc and 80 mg/l iron (BHP Gold, New Zealand, unpub. company report, 1988), may reflect this type of situation.

Seepage from poorly consolidated tailings piles may be more acidic. Small volumes of water seeping from tailings in the Cariboo district, British Columbia has a pH of 2.7 and contains 556 µg/l arsenic and elevated abundances of cadmium, copper, lead, and zinc (Azcue and others, 1995). Seepage from sulfide mineral concentrates at an abandoned mill site, of the Treadwell, southeastern Alaska, mines has a pH of 2.9 and contains 330 mg/l iron, 2500 µg/l zinc, 380 µg/l copper, 160 µg/l cobalt, 100 µg/l nickel, 32 µg/l cobalt, and 21 µg/l lead (R.J. Goldfarb, unpub. data, 1995).

Mercury, which is used for gold extraction, is extremely enriched in sediment and fish tissue in drainages downstream from many historic low-sulfide gold mines (Callahan and others, 1994). Down-river from present-day gold mines in Brazil, mercury abundances are as much as 20 ppm in sediment, 2.7 ppm in fish, and 8.6 µg/l in water (Pfeiffer and others, 1989). Down-river from the California Mother lode veins, dredged river sediment contains as much as 37.5 ppm mercury and surface and ground water contains 13 to 300 µg/l mercury (Prokopovich, 1984). Extreme mercury abundances have been documented in sediment in drainages of the Carolina slate belt and the Dolgellau gold belt, Wales, more than 75 years after cessation of mining (Fuge and others, 1992; Callahan and others, 1994). Unfiltered and filtered samples of water draining tailings piles in the Fairbanks, Alaska, district contain as much as 0.58 and 0.11 µg/l mercury, respectively (R.J. Goldfarb, unpub. data, 1995).

Metal mobility from solid mine wastes

Acid mine drainage problems are probably restricted to water that infiltrates untreated mine dump piles. In temperate climates, initial spring snow melt draining dumps is likely to contain significant heavy metal abundances, including arsenic, iron, and antimony, and less commonly lead and zinc, mainly due to dissolution of soluble salts accumulated during winter. In most cases, small volume acidic effluent seeping from waste piles is diluted to background abundances upon entering adjacent stream channels; consequently, environmental impact is restricted to surface channels upstream from their intersections with the nearest, major surface waterway.

Arsenic is usually the trace element of greatest environmental concern in soil associated with mine tailings. Inadvertent soil ingestion by young children and arsenic-rich household dust pose potential risks to human health. These risks have become serious public issues in parts of the California Mother Lode belt where housing projects have been developed on soil derived from old mine tailings (Time, September 25, 1995, p. 36). Secondary, arsenic-bearing salt minerals, and to a lesser extent, relatively insoluble arsenic-bearing sulfide minerals, become bioavailable primarily by adsorption from the fluid phase in the small intestine. Geochemical factors that control arsenic bioavailability from soil include the type of arsenic-bearing mineral, the degree of encapsulation of that mineral in an insoluble matrix, the nature of alteration rinds on mineral grains, and the rate of arsenic dissolution in the gastrointestinal tract (Davis and others, 1992).

Soil, sediment signatures prior to mining

Arsenic concentrations in soil and sediment are about 50-1,000 ppm near unmined deposits; background abundances elsewhere are typically 10-40 ppm. Antimony levels are commonly >5 ppm near deposits, whereas they are normally <2 ppm in areas unaffected by hydrothermal activity (Bowell and others, 1994; R.J. Goldfarb, unpub. data, 1995).

Potential environmental concerns associated with mineral processing

Summarized from Ripley and others (1995).

(1) Mercury amalgamation, commonly used in historic gold extraction processes, may have deposited significant amounts of mercury in tailings piles. Where amalgamation is still used, volatilized mercury generated by the process may significantly affect air quality because as much as ten percent of the mercury used is lost to the atmosphere.

(2) Most cyanide used for gold extraction is recovered and recycled, but some inevitably remains in tailings liquor and can leak into regional ground water networks. Any loss of cyanide to the environment is a major concern because it is toxic to a wide variety of organisms. Many mills now use chemical-treatment systems to convert hazardous cyanide compounds to insoluble compounds that are not bioavailable. This is especially critical in cold climates where natural volatilization of cyanide from holding ponds is relatively slow.

(3) Where heap-leaching methods are employed, environmental risks are greater. Leakage and erosion risks are greatly increased, as are risks to wildlife, because cyanide leaching is usually done outdoors. *In situ* leaching, if applied to relatively impermeable orebodies, could result in local aquifer contamination.

(4) Roasting ore that contains abundant sulfide minerals emits significant amounts of arsenic trioxide and other metal oxides into the atmosphere.

(5) Highly acidic effluent is produced during sulfide bio-oxidation. Without proper neutralization or during spills, this effluent can be extremely hazardous.

(6) Crushing and grinding ore may present noise and dust hazards.

Smelter signatures

Ore derived from these deposits is not smelted.

Climate effects on environmental signatures

In dry and seasonally wet climates, the potential for generating small-volume pulses of significantly metal-enriched acid mine drainage is enhanced by evaporation and soluble salt accumulation. In wet climates, increased surface runoff enhances dilution and may mitigate peak acid and heavy-metal concentrations that characterize mine drainage in dry and seasonally wet climates.

Geoenvironmental geophysics

Wide-band electromagnetic systems can be used to identify major shears associated with veins that may serve as major ground water conduits. Direct current and electromagnetic resistivity and magnetic surveys can be used to study porous rock associated with faults and shear zones that may control ground water flow. Within and downslope from mine areas, low-resistivity acid- or metal-bearing water can be identified with electromagnetic or direct current induced polarization/resistivity surveys and ground penetrating radar. Structural and stratigraphic features such as bedrock topography, buried channels, and aquitards that affect water flow away from mine areas may be studied with electromagnetic or direct current resistivity, seismic refraction, and gravity surveys. Stratigraphic details in shallow sand and gravel water pathways can be investigated with seismic reflection and ground penetrating radar. Water flow may be monitored using self potential.

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