Chapter K

GEOENVIROMENTAL MODEL FOR LOW-SULFIDE GOLD-QUARTZ VEIN DEPOSITS

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Deposit geology

These deposits include quartz and quartz-carbonate veins mined primarily for gold. They are found in accreted terranes dominated by greenstone and slate sequences that have been metamorphosed to greenschist, or less commonly to amphibolite or granulite facies (Berger, 1986a; Goldfarb and others, 1995). These veins generally contain no more than a few percent sulfide minerals. Wall rocks, which in some deposits include disseminated ore bodies, contain abundant carbonate minerals, quartz, sericite, and sulfides. Mineralization is commonly associated with regional shear zones, which may include melange zones with varied lithologies and tectonically-emplaced ultramafic rocks and serpentinite. Deposits spatially associated with plutonic rocks tend to have more varied suites of metals, and are more likely to contain more silver and to yield copper, lead, and zinc as byproducts. Arsenic is the minor element most commonly enriched in alteration haloes. These deposits are also known as mesothermal, Mother Lode-type, orogenic, metamorphic rock-hosted, shear zone-hosted, greenstone-hosted or greenstone gold, turbidite-hosted, and slate-belt gold (Groves and others, 1998).

Low-sulfide gold-quartz veins are found in deformed metamorphic rocks of all ages, world-wide; they are the most widespread type of gold-bearing mineral deposit. Since the late 1970's, accreted terranes of all ages in the United States have been explored for these deposits, resulting in production from the southern Appalachians, the Lake Superior region, the Sierra Nevada region of California, and southeastern and central Alaska. Individual deposits have yielded from a few tonnes to more than 100 tonnes of gold.

Examples

Yilgarn Block, Western Australia; Abitibi Belt, Superior Province, Canada; Yellowknife, Northwest Territory, Canada; Bendigo/Ballarat, Victoria, Australia; Murantau, Uzbekistan; Otago Schist Belt, South Island, New Zealand; Sierra Nevada (including Mother Lode), California; Juneau Gold Belt, Alaska; Tintina Gold Belt, Alaska; Slate Belt, North and South Carolina; Dahlonega Belt, Georgia; Virginia Gold-Pyrite Belt, Virginia.

Related deposit types

The deposit type most closely related genetically to low-sulfide gold-quartz veins is Homestake gold (Berger, 1986b; Klein and Day, 1994), which is produced by similar hydrothermal systems superimposed on Precambrian iron formation host rocks. Related deposits found at shallower depths in accreted terranes include gold-antimony deposits (Berger, 1993), and silica-carbonate mercury deposits (Rytuba, 1986). Either of these deposit types could conceivably represent the near-surface expression of the hydrothermal systems that produce low-sulfide gold-quartz lodes at depth (fig. 1). All these deposits form from carbonic fluids derived from metamorphic dewatering reactions.

Volcanogenic massive sulfide deposits of all types (Cyprus, Kuroko, and Besshi; see Singer, 1986a, 1986b; Cox, 1986b) are spatially associated with, but not genetically related to, low-sulfide gold-quartz veins, because both are found in greenstone or greenstone-slate terranes. Podiform chromite deposits (Albers, 1986) may be spatially associated in regional shear zones that host ultramafic rocks as well as low-sulfide gold-quartz veins. Polymetallic vein deposits (Cox, 1986a) may also be spatially associated, especially where plutons intrude accreted terranes. Indeed there may be a continuum between low-sulfide gold-quartz veins produced by fluids that show no clear evidence of magmatic fluid contributions, and precious-metal bearing polymetallic veins produced by alkali chloride-rich magmatic-dominated fluids. For example, deposits of the Tintina Gold Belt, Alaska and Yukon, although spatially and temporally associated with the mid-Cretaceous Tombstone and Tungsten plutonic suites, have many characteristics in common with low-sulfide gold quartz veins (Lang and others, 2000; Goldfarb and others, 1997a), and are included in this geoenvironmental model.
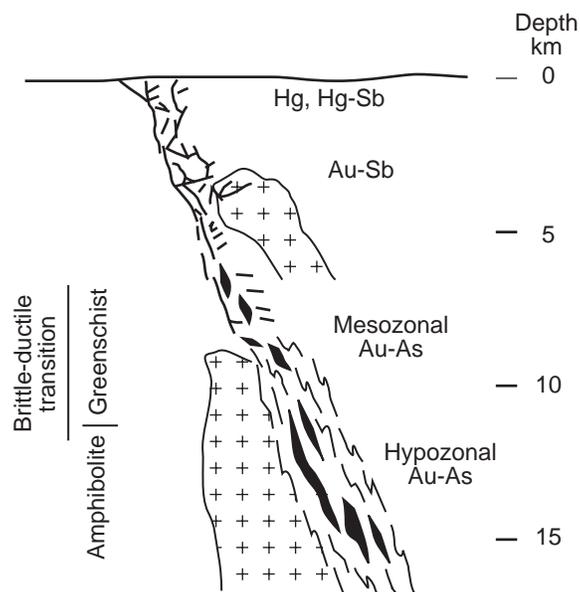
Figure 1. Schematic representation of shear-zone setting of low-sulfide gold-quartz veins and related deposits. Mod-ified from Groves and others (1998), and McCuiag and Kerrich (1998).

In almost all areas where low-sulfide gold quartz veins are exposed, gold released by erosion is concentrated in placers (Yeend, 1986). In regions where erosion is deep and geomorphic history is favorable, as in the Sierra Nevada and Klamath Mountains, California, and Seward Peninsula, Alaska, the bulk of the gold endowment may be found in the placer deposits. Low-sulfide gold-quartz vein deposits subjected to deep tropical or temperate-humid weathering can produce lateritic or saprolitic (eluvial placer) deposits (McKelvey, 1992).

<u>Deposit size</u>

The size of low-sulfide gold-quartz deposits varies considerably from region to region. Archean deposits are the largest, but their greater median size may be the result of particularly favorable regional tectonic and structural features rather than any factors directly related to age. Table 1 shows summary statistics for four tonnage models available for various groups of low-sulfide gold-quartz veins. It is important to note that some historic deposits include mineralized wall rock (called "gray ore" in the Sierra Nevada), which usually results in higher tonnages and lower grades, and many recently mined deposits have exploited bulk-minable mineralized wall rock or densely-veined stockworks. The historic disseminated deposits are included in the present models, whereas many recently-mined deposits are not included.

Table 1

Deposit group	Median size, million mt	90th %tile size, million mt	10th %tile size, million mt	Reference
Archean	1.1	0.089	13	Klein & Day, 1994
Phanerozoic	0.03	0.001	0.91	Bliss, 1986
California (Mesozoic)	0.025	0.0008	0.78	Ashley, unpub (derived from Bliss, 1986)
Chugach, AK (Cenozoic)	0.0032	0.0004	0.026	Bliss, 1992

Mafic to intermediate metavolcanic rocks (greenstones) are the most important host rocks for low-sulfide gold-quartz veins, especially in the case of the Archean deposits. Slate and graywacke are also important hosts, especially in Phanerozoic rocks. Ultramafic rocks and serpentinite occur in some mineralized shear zones. Pre-ore plutons may also host deposits. Carbonate and other types of sedimentary rocks are not usually associated with low-sulfide gold-quartz deposits, but may occur locally in melange belts associated with mineralized regional shear zones. Some ore minerals and alteration minerals are restricted to certain host rock types, whereas others are always present regardless of rock type, and still others vary from deposit to deposit but are not associated with any particular rock type.

Surrounding geologic terrane

Most low-sulfide gold-quartz deposits occur in highly-deformed metamorphosed accreted volcanic-sedimentary terranes of greenschist facies, but ranging from sub-greenschist to granulite facies. Many deposits, especially the larger ones, are associated with major regional shear zones. High-angle faults that either splay from, or are cut by, these major shear zones are commonly sites of mineralization. Synkinematic and late-kinematic intermediate to felsic plutons are common in accreted terranes, and usually pre-date gold mineralization. Serpentinized ultramafic rocks and dikes of all compositions may be associated with the shear zones.

Unaltered greenschist-facies metavolcanic and metasedimentary rocks usually have moderate buffering capacity because mineral assemblages include albite, mica, chlorite, epidote, and carbonate, and may include relict pyroxenes and amphiboles. Slates, on the other hand, may contain disseminated sedimentary pyrite or pyrite porphyroblasts. Rocks in the contact aureoles of plutons, which usually reach amphibolite grade, tend to have lower buffering capacity.

Wall-rock alteration

Alteration zones are always present, and are generally better developed in metavolcanic rocks than in slates. Widths of alteration zones vary with lithology, size of the vein system, and abundance of minor faults. Alteration can extend away from deposits for many kilometers along shear zones and fault zones. Carbonic hydrothermal fluids replace calcium, magnesium, and iron silicates of the wall rocks with carbonate minerals, and add potassium mica, quartz, and sulfides. Components most notably added are CO_2, H_2O, potassium, and sulfur. Silica may be added, or redistributed from wall rocks into veins. Hydrothermal carbonate minerals include dolomite, ankerite, magnesite, siderite, and calcite. Although the dominant carbonate mineral is frequently described as ankerite, it is usually ferroan dolomite. Assemblages vary with host rock lithology (Böhlke, 1989). Typical assemblages include ferroan dolomite, albite, quartz, potassium-mica, chlorite, pyrite, and arsenopyrite. Albite is particularly abundant in altered granitic rocks. Assemblages in altered serpentinite also include talc, magnesite, and fuchsite/mariposite, and lack albite.

Nature of ore

Individual veins are generally 1 to 10 meters wide and less than a few hundred meters long, but ore-bearing zones are typically larger, and include multiple veins. Veins and ore zones are equally persistent laterally and vertically, and most deposits show no notable vertical or along-strike zoning of vein minerals, ore minerals, or alteration minerals. Among deposits that show such zoning, patterns vary from deposit to deposit.

Veins commonly show ribbon texture or contain wall-rock fragments. In typical ore, both gold and sulfide grains occur scattered through the quartz, but gold tends to be concentrated at the margins of the ribbons and wall-rock fragments, whereas sulfides tend to be concentrated within the ribbons and fragments. Some gold is associated with sulfides, located on grain boundaries or on microfractures within grains, or forming inclusions. Proportions of gold associated with sulfides vary; e.g., in Sierra Nevada deposits, typically about two-thirds of the gold occurs as isolated, free-milling grains, and the rest is intimately associated with sulfides. The most common minor sulfide minerals are galena, sphalerite, and chalcopyrite. Carbonate in the veins tends to occur in discrete growth bands, commonly near or at the vein

178

walls. High-grade ore consists of coarse crystalline or leaf gold intergrown with quartz, commonly with no associated sulfide minerals (e.g., Nelson and Leicht, 1994).

Parts of the alteration zones may contain enough gold to be ore-grade. Sulfides, especially pyrite and arsenopyrite, tend to be more abundant in such disseminated ore, as much as about 10 percent, and gold grades are generally lower than in veins (e.g., data for deposits of the Yilgarn Block, Western Australia, in Ridley and others, 1996). Sulfides also tend to be more abundant in altered rocks that host stockworks. In many districts ore bodies are restricted to veins. In some districts both ore-bearing veins and disseminated ore occur, and in a few districts the veins are low-grade or even barren, and the ore bodies are restricted to altered wall rocks.

Mining and ore processing methods

Because low-sulfide gold-quartz veins are relatively small and high-grade (e.g., the tonnage-weighted average gold grade for historic mines in California is about 14 g/tonne), underground methods were used in most historic mines, and are still used in the majority of active mines worldwide. Because these deposits are equally likely to extend to depth or laterally (see above), they were not effectively exploited until the 1870's, when several technological developments (steel cable, improved explosives and power drills) permitted efficient development and ore removal. It has long been common practice to use waste rock from underground development drifts to backfill stopes, especially where the ground is unstable or timber is expensive. Developments in milling technology also had an impact on mining methods, as efficient classifiers developed in the late 1800's allowed coarser tailings (sands) to be separated and used underground as backfill. Thus at some mines a significant proportion of the waste rock and ore processed (but not more than 50 percent) was disposed of underground rather than on the surface.

From the early 19th century to World War II the most common device used world-wide for fine ore crushing and pulverizing was the stamp mill (Richards, 1918). It consisted of cylindrical mortars raised by rotating cams and allowed to drop on dies set in an enclosure called a battery box, into which coarsely crushed ore, water, and mercury were fed. The recommended amount of mercury in early practice was 2 to 3 avoirdupois ounces (57 to 85 grams) per troy ounce gold to be saved (Churchill, 1999a), and 1 to 2 avoirdupois ounces (28 to 57 grams) in later practice (Dufourcq, 1918). Thus the maximum possible loss of mercury into tailings for ore with an anticipated grade of 0.5 troy ounce free-milling gold per avoirdupois ton would be about 43 grams per ton (47 g/tonne). In practice, of course, the mercury that formed amalgam was recovered and recycled. The pulp produced in the battery box was discharged through a screen onto secondary plates coated with mercury, to catch any gold that escaped amalgamation in the battery box. Most mercury loss occurred in the battery box, owing to "flouring" caused by the battering action of the stamps. Flouring refers to breakup of mercury into very fine particles, which will not amalgamate or reunite. Around 1890 in California, mercury losses into mill tailings averaged 14 grams per avoidupois ton (Churchill, 1999a). At mines where amalgamation was employed, the amalgam was usually retorted on site to produce sponge gold and recover mercury for reuse. Areas around retort sites are likely to have mercury contamination.

As cyanidation was introduced beginning in the early 1890's, milling practices changed. For efficient cyanidation, finer pulverizing was needed than could be achieved economically with stamp mills, but most mines chose to keep their stamp mills rather than invest in completely new equipment, adding grinders of various types to achieve the necessary fine grinding. The stamps were used for coarser crushing, greatly reducing the time that pulp remained in the battery box, and many mills abandoned battery box amalgamation entirely. By about 1910, typical mercury losses had been reduced to 2-3 grams per avoirdupois ton (Finlay, 1918).

If mercury is present in pulp subjected to cyanide leaching, some will dissolve, although not enough to consume significant cyanide (Dufourcq, 1918). At the Kennedy and Argonaut mines, Amador County, California, some tailings that were subjected to amalgamation were reprocessed using cyanidation. Mercury concentrations in the reprocessed tailings are not significantly lower than those in the original tailings (Dames & Moore, 1995; R. Ashley and D. Ziarkowski, unpub. data), indicating that except perhaps in unusually Hg-rich samples, cyanidation does not result in significant removal of mercury from tailings. However, mercury taken into cyanide solution will precipitate with gold when zinc is added, with the result that mercury contamination could be found around sites of refining furnaces, where precipitates were

smelted to produce bullion. Cyanide itself is generally not a problem because it degrades rapidly under oxidizing conditions (U.S. Bureau of Mines, 1994).

The flotation process, installed at some gold mines beginning in the 1930's to remove and concentrate sulfides (which were often shipped to regional smelters), resulted in another class of processing chemicals being introduced to mill sites and tailings. Most compounds used for flotation, however, are organic compounds that are not highly toxic or persistent, and before World War II only a few reagents were used (mainly pine oil and xanthate; U.S. Bureau of Mines, 1994).

Modern milling practice involves grinding of ore in various types of rotary mills, usually ball mills, separation of free gold by gravity concentration, and cyanidation with adsorption of the gold on activated carbon; mercury is no longer used. Mercury is still used, however, in small operations in less developed countries.

To predict composition of mill tailings and their environmental impacts, it is essential to know whether and how sulfide minerals were treated in the milling process. At one extreme, they may have been ignored, and therefore not removed but reduced to small, highly reactive particles that were passed to the tailings. On the other extreme, they may have been separated, concentrated, and shipped to an off-site smelter, so that only a small fraction of the sulfide was passed to tailings. Such residual sulfide, however, tends to be dominated by the extremely fine particles that could not be captured, which will decompose very rapidly and release metals when exposed to oxidizing conditions. Where it is not economic to remove and concentrate sulfides, or operators do not have the necessary know-how to do so, the ore may be roasted. Uncontrolled roasting of sulfides results in dispersal of airborne sulfur gases and toxic metals, including arsenic and lead.

Trace element geochemistry

In addition to gold and silver, minor elements most strongly enriched in low-sulfide gold-quartz deposits include arsenic, antimony, tellurium, selenium, tungsten, molybdenum, bismuth, and boron (Berger, 1986a; McCuaig and Kerrich, 1998). The degree of enrichment of these elements varies greatly among regions, and within regions and districts, but usually not much within deposits. The gold-silver ratio averages 5:1 (McCuaig and Kerrich, 1998). The element most consistently enriched along with the precious metals is arsenic; arsenopyrite and arsenian pyrite are frequently reported (Bliss and Jones, 1988; Klein and Day, 1994; Clark, 1970; Savage and others, 2000). Enrichment factors for gold range from about 1,000 to 10,000 for most deposits, and factors for arsenic range from about 100 to 10,000 (McCuaig and Kerrich, 1998; Ashley and Ziarkowski, 1998; Savage and others, 2000).

Figure 2 shows arsenic concentrations in ore-grade rocks from several districts in the Sierra Nevada, California. The lower cut-off of 1 g/tonne gold is arbitrary; material of this grade is processed in modern open-pit mining operations, but minimum grades of ores processed at historic mines were probably higher. Because arsenic was not recovered from the ores, the plot provides an indication of maximum amounts of arsenic to be expected in mining wastes. It shows that amounts of arsenic in ore-grade materials vary greatly, from less than 10 g/tonne to more than 1 percent, and ores from individual mining districts show distinctive ranges of arsenic values. With the possible exception of the Alleghany district, however, arsenic concentrations do not increase notably with increasing gold grade.

In the Jamestown and Hodson districts, California, where the ores have relatively little arsenic, altered wall rocks (<1 mg/kg gold) have about the same amounts of arsenic as ores, whereas in the districts where arsenic is more abundant in the ores, altered wall rocks have less arsenic than ores.
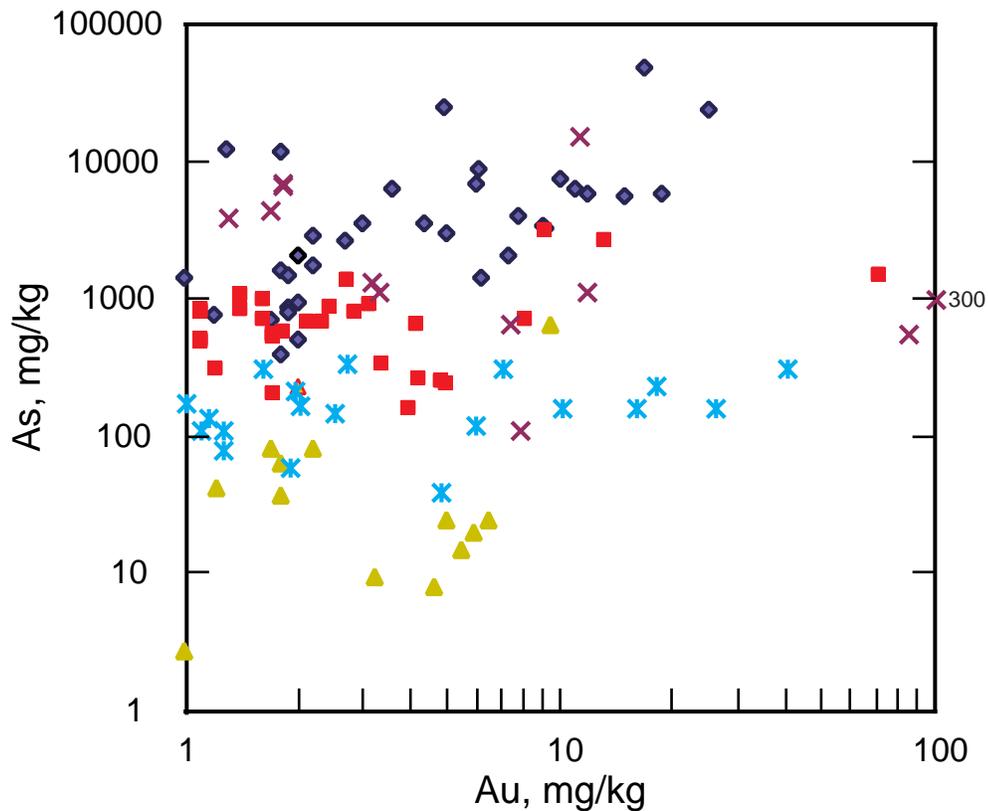
Relatively few high-quality analyses are available for mercury in low-sulfide gold-quartz deposits. Data compiled for the same Sierra Nevada districts as above show no enrichment in ores in some districts and maximum enrichment factors generally less than 20 in others, and no enrichment in altered wall rocks with low gold grades in any district (Ashley, 1999b, 2000; figure 3).

The base metals lead, copper, zinc, and cadmium are commonly present in accessory sulfides (galena, chalcopyrite and sphalerite), but enrichment factors are generally less than 10, and in some deposits one or more of these elements may be depleted relative to average crustal abundance (McCuaig and Kerrich, 1998).

Other elements that may show enrichment in low-sulfide gold-quartz deposits include chromium, nickel, cobalt, vanadium, platinum-group elements (PGE), and scandium. Modest enrichment of these elements in deposits hosted by greenstone or slate may be attributed to hydrothermal scavenging from
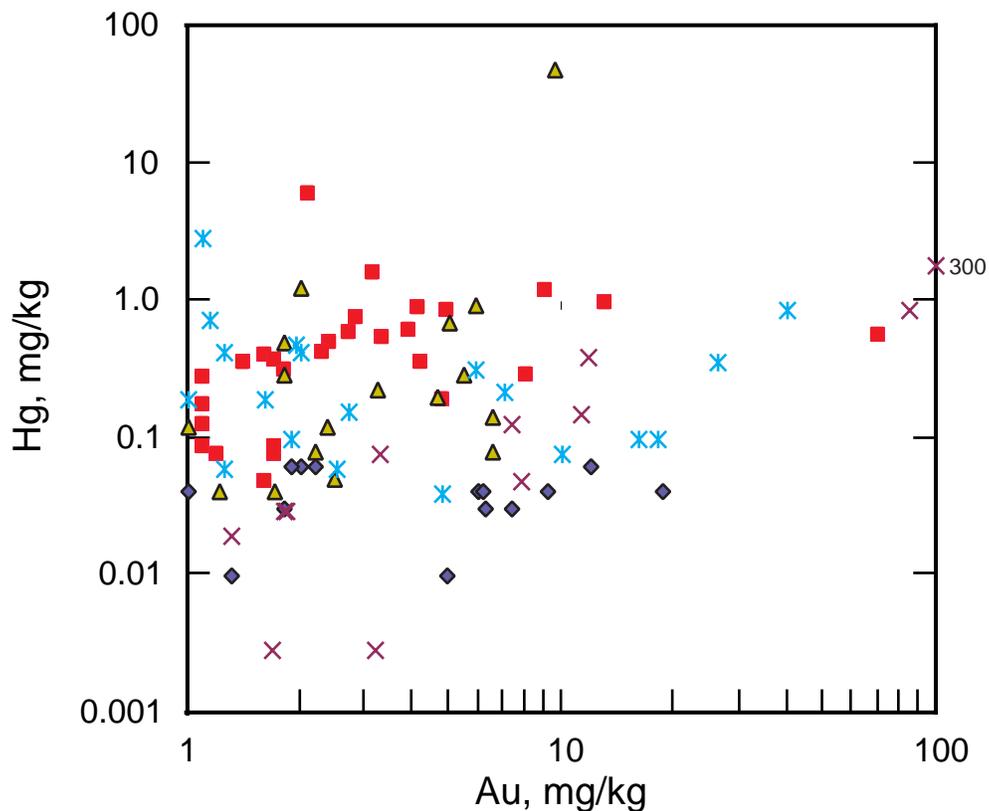
metavolcanic rocks in the host terrane (Gao and Kwak, 1997). Chromium, nickel, and cobalt may be substantially enriched in deposits in which host rocks include altered ultramafics and serpentinite. The chromium is retained in fuchsite/mariposite, and nickel and cobalt form accessory sulfides, arsenides, and sulfarsenides, including millerite, niccolite, gersdorffite, loellingite, and cobaltite (Savage and others, 2000a).

   Wall-rock alteration in rocks of the greenschist facies involves addition of large-ion lithophile elements (LILE; McCuaig and Kerrich, 1998; Groves and others, 1998). This group of elements includes potassium, rubidium, barium, lithium, cesium, and thallium. The only element of possible environmental concern here is thallium. Analytical data for thallium are scarce, but absolute values appear to be generally low (a few ppm; R. Ashley, unpub. data). Alteration produces little change in rare-earth elements (REE) or in the minor high field-strength elements (HFSE), including titanium, zirconium, niobium, tantalum, yttrium, gallium, thorium, and uranium (McCuaig and Kerrich, 1998, Gao and Kwak, 1997; Bierlein and others, 1999).

◆ Alleghany district (Böhlke, 1986)

■ Shingle Springs district (Nash, 1988)

✖ Hodson district (Chaffee and Sutley, 1994)

▲ Harvard mine, Jamestown district
   (Ashley, unpub. data)

✕ N. Mother Lode districts (Sutter Cr., Nashville,
   Kelsey, Spanish Flat; Ashley, unpub. data)

Figure 2. Arsenic concentrations in ores from selected gold districts, Sierra Nevada region, California.

Figure 3. Mercury concentrations in ores from selected gold districts, Sierra Nevada region, California.

Legend:
- ◆ Alleghany district (Böhlke, 1986)
- ✕ Northern Mother Lode districts (Sutter Creek, Jackson, Nashville, Kelsey, Spanish Flat, Nevada City; Ashley, unpub. data)
- ■ Shingle Springs district (Nash, 1988)
- ✳ Hodson district (Chaffee and Sutley, 1994)
- △ Harvard mine, Jamestown district (Ashley, unpub. data)

Primary mineralogy and zonation

In most low-sulfide gold-quartz deposits native gold containing 15 to 20 weight percent silver is the ore mineral, and neither gold nor silver occur in any other minerals. In most deposits tellurides are scarce or absent, but in a few deposits they account for much of the gold and silver (Clark, 1970). In some relatively base-metal rich and high-silver deposits, silver may occur in sulfosalts (ruby silvers) and tetrahedrite (freibergite) (Ashley and Ziarkowski, 1999).

The important ore-related minerals, listed in decreasing order of frequency reported, are pyrite, galena, arsenopyrite, chalcopyrite, sphalerite, pyrrhotite, stibnite, tetrahedrite, and scheelite (Bliss and Jones, 1988). All of these minerals except scheelite can potentially generate acid and release metals. Among them, pyrite is commonly the most abundant. Galena, arsenopyrite, and pyrrhotite are commonly second in abundance (pyrrhotite tends to be relatively abundant if it is present at all). Chalcopyrite, sphalerite, and tetrahedrite are subsidiary in abundance. Stibnite and scheelite vary greatly from deposit to deposit, (Bliss

and Jones, 1988). Bismuth and boron, which occur in bismuthinite and tourmaline respectively, each tend to be characteristic of certain gold regions or mineral belts.

Because total sulfide contents are generally less than 5 percent in veins and 10 percent in disseminated ores, and carbonate minerals are abundant (variable in veins, but 5 to 15 percent or more in altered wall rocks), the bulk mineralized rock is generally well buffered. As stated above, consistent zoning patterns are not observed, although unusual concentrations of certain minerals, particularly scheelite, molybdenite, or tellurides, are reported from certain veins or stopes within individual mines.

Arsenian pyrite may be fairly common in low-sulfide gold-quartz deposits, especially where arsenopyrite is scarce or absent, although it may not always be recognized and reported. The arsenic content of such pyrite is generally less than 2 weight percent, but individual grains may contain as much as 4 weight percent (Savage and others, 2000a; 2000b).

Secondary mineralogy

Much work has been done on weathered residual soils over low-sulfide gold-quartz veins and their alteration haloes, for geochemical exploration. The focus of these studies has been on bulk mineralogy and behavior of minor elements with respect to various leaches. Less attention has given to identifying specific binding sites and binding mechanisms for minor and trace metals and metalloids.

Where iron is abundant and sulfate scarce, scorodite forms. Locally pyrite oxidation may produce conditions sufficiently acidic to form jarosite, especially in pyritic slates with relatively low carbonate contents, and significant amounts of arsenic can substitute in such jarosite (Savage and others, 1999; Savage and others, 2000a). Typically, however, weathering involves formation of iron oxyhydroxide minerals, especially goethite, which adsorb arsenic (Smith and others, 1994; Foster and others, 1998) and significant proportions of available transition metals and other metalloids (Plumlee and others, 1999). Details of the mechanism of pyrite oxidation in carbonate-buffered solutions have been extensively investigated (e.g., Evangelou and others, 1998). Arsenian pyrite oxidizes more rapidly than arsenic-free pyrite (Plumlee and others, 1999).

Oxidation of low-grade ore and sulfide-bearing altered rock exposed in mine workings, walls of open pits, and waste rock piles should ultimately result in mineral assemblages similar to those in natural outcrops. Until oxidation is complete, however, soluble efflorescent salts form during dry periods. Because acid generated by decomposing sulfides reacts promptly with carbonates, releasing calcium and magnesium, efflorescent salts are dominated by epsomite, hexahydrite, and gypsum (R. Ashley and K. Savage, unpub. data). Locally, however, hydrated ferric sulfates that store metals, especially copiapite and jarosite, may also form (Savage and others, 2000). It appears that significant amounts of arsenic may be associated with the iron-free salts, possibly owing to formation of hydrated calcium arsenate minerals (K. Savage, unpub. data). Calcite/aragonite dripstone forms on some pit walls and underground workings. The same efflorescent minerals form on tailings. Where sulfides have been removed during milling, ferric sulfates do not form, but usually enough sulfate remains to form hydrated calcium and magnesium sulfates. Where sulfide concentrates have been stockpiled, efflorescent salts form similar to those that form on other metal sulfide-rich ores (R. Ashley, unpub. data).

Pre-mining soil and sediment signatures

Arsenic concentrations in soils overlying unmined deposits reach about 1,000 ppm, and concentrations in soils over surrounding alteration zones range from tens to several hundreds of ppm (Savage and others, 2000a, 2000b; Sutter Gold Mining Company, unpub. data; Bowell and others, 1994). Although gold itself is the primary target element in geochemical soil-sampling exploration programs, arsenic has been used as a pathfinder element. Antimony may also show anomalies.

Deep and intense weathering of deposits removes most geochemical signatures except for gold itself. Low-sulfide gold-quartz veins are likely the ultimate source of gold in most economic laterite-saprolite gold deposits. Residual enrichment of arsenic, lead, tin, and scandium has been noted along with iron, aluminum and gallium in ferruginous zones that form near the surface in laterite-saprolite gold deposits (McKelvey, 1992).

Anomalous concentrations of REE and HFSE have been observed in soils overlying deposits, even though these elements are not enriched in ores or altered rocks. The anomalies have been attributed to

release of these elements from dissolution of accessory minerals, particularly apatite, resulting from the breakdown of sulfides during oxidation (Bierlein and others, 1999).

Topography and physiography

Many deposits are located in belts within Precambrian cratons and are poorly exposed, showing no topographic expression. In continental margin tectonic settings (e.g. California, southeast Alaska), resistant low-grade or barren quartz veins ("bull veins"), which may be found in the same fault zones as productive veins, are likely to be prominently exposed. Ore-bearing veins are rarely well exposed, owing to presence of ribbon structure, wall-rock fragments, carbonate-rich bands, and vugs. Vuggy textures are enhanced by weathering of sulfides. Alteration zones, because they are heterogeneous and carbonate- and sulfide-bearing, also tend to be poorly exposed, especially where associated with shear zones or melange.

Hydrology

Fault zones that localize low-sulfide gold-quartz veins vary greatly in permeability and hydraulic conductivity. In the Sierra Nevada foothills of California, where a large rural population depends upon domestic water wells, some areas with poor water quality (owing to high levels of sulfate and hardness) correlate with gold mineralization and associated altered rocks (California State Water Resources Board, unpub. data; Sonora Mining Corporation, unpub. compilation of water well data from County of Tuolumne, California). High levels of arsenic could be present in domestic wells in these areas, but to date no specific cases clearly related to gold mineralization have been documented or publicized.

Three pit lakes at two recently mined deposits in the Sierra Nevada foothills (Skyrocket and North pits at the Royal-Mountain King mine, and Harvard pit at the Jamestown mine) have pH values between 7.0 and 8.1, arsenic concentrations between 100 μg/L and about 1 mg/L, sulfate concentrations between about 500 and 1200 mg/L, and very low iron concentrations (Meridian Gold Company, 1997; Ashley and Savage, 2001, figures 4 and 5). Although there are complicating factors including evapo-concentration and contributions from rain-water runoff and process waters, the pit lakes provide an indication of what might be expected in ground waters affected by mineralized rocks undergoing oxidation.
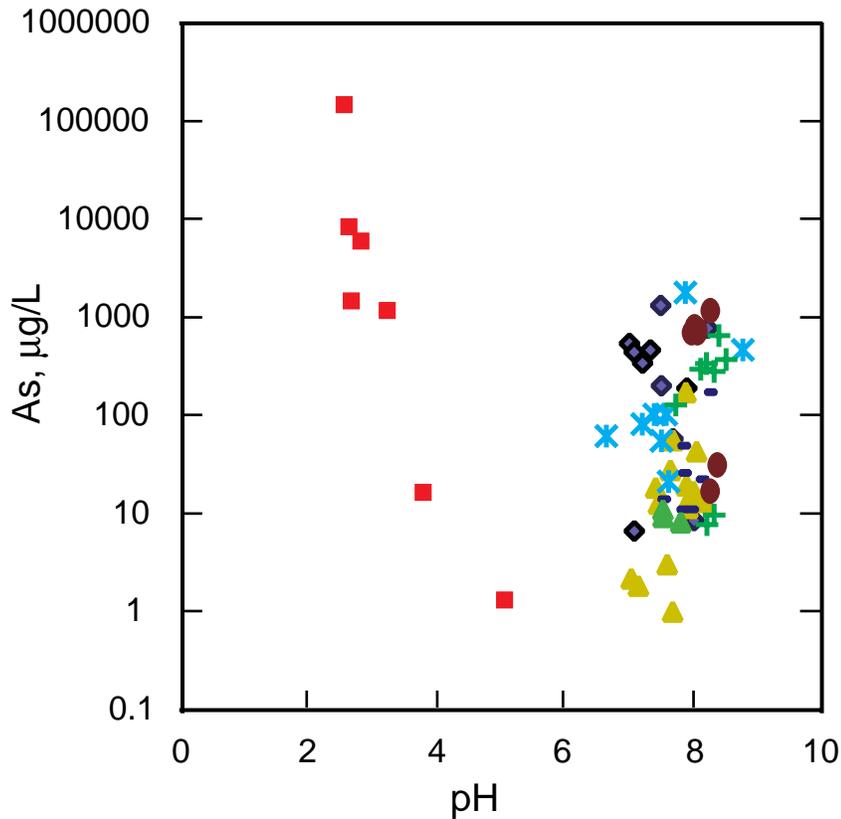
The Harvard pit, which exploited ore bodies on the Melones Fault Zone in the southern Mother Lode belt, Tuolumne County, California, demonstrates possible complexities of hydrologic regimes around low-sulfide gold deposits. Since the pit was abandoned in 1994 at a depth of about 160 m, the pit has been filling rapidly, mainly from sulfate-rich but arsenic-poor water entering along open low-dipping fractures in the slate of the hanging-wall. Elevated arsenic levels (about 1 mg/L) in the lake, however, indicate that there are significant contributions from oxidizing sulfides, and suggest that water also enters the pit after traversing hydrothermally altered rocks in the Melones Fault Zone.

The best example of elevated arsenic in ground water that may be related to gold mineralization is the Fairbanks area, Alaska, where many inhabitants rely on ground water from private domestic wells. Natural background concentrations as high as 10 mg/L have been measured (Wilson, 1975; Hawkins and others, 1982). The source for the arsenic remains unclear, although it is generally assumed to reflect dissolution of widespread arsenopyrite and its oxidation product, scorodite. The area is mainly underlain by schist of Late Proterozoic to early Paleozoic age which was intruded by felsic to intermediate plutons at about 90 Ma. Widespread hydrothermal fluid flow associated with this thermal event was responsible for abundant gold vein formation (McCoy and others, 1997). The areas of highest arsenic in ground waters are not spatially associated with known gold occurrences, but abundant sulfide minerals disseminated in the schist indicate that the 90 Ma hydrothermal event was likely responsible for very widespread sulfidation of some strata. Disseminated arsenopyrite and pyrite are the most likely sources for the ppm-level arsenic concentrations in water. Background levels of dissolved arsenic in stream and spring waters from most areas underlain by the schist are <5 μg/L (Goldfarb et al., 1999), but these levels increase by 2 to 3 orders of magnitude locally. Dissolved antimony (≤50 μg/L), manganese (≤5.6 mg/L) and/or iron (≤2 mg/L) are also elevated in some but not all of the arsenic-rich (0.5 to 10 mg/L) waters (Farmer and others, 2000). Values for pH, however, are near neutral (6.3 to 7.5; Mueller and others, 2000).
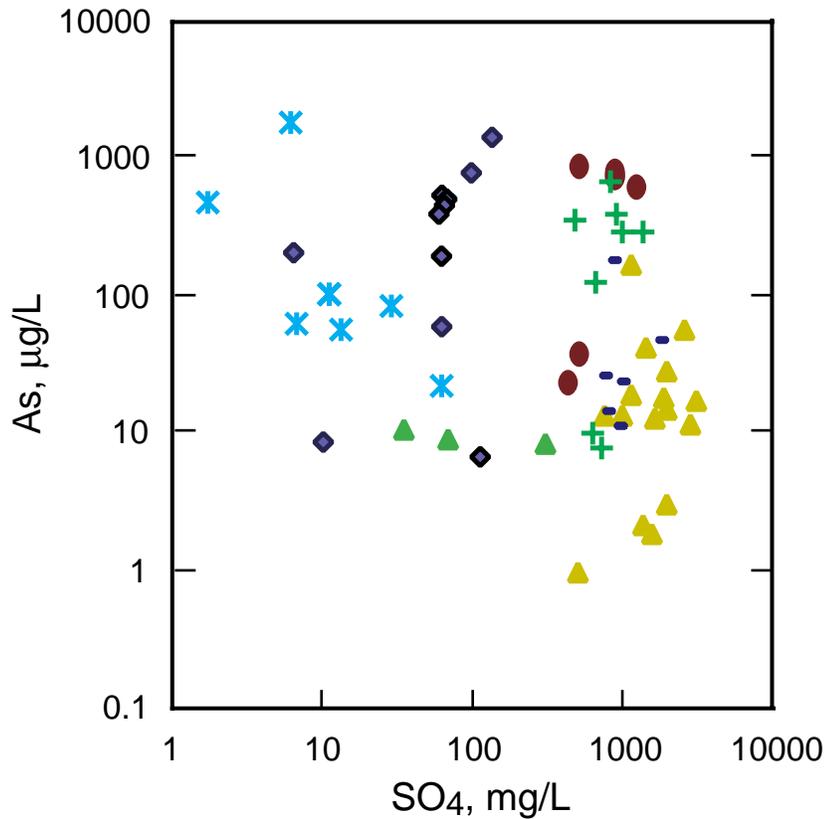
Drainage signatures

Owing to low sulfide content of ores and buffering capacity of carbonates associated with mineralization, significant acid drainage is generally not associated with this deposit type, and base-metal loadings are consistently low. Near-neutral sulfate-bicarbonate waters that result from contact with these

184

ores and altered rocks, however, are effective for mobilizing metalloids and metals that form oxyanions, including arsenic, selenium, antimony, and molybdenum. The following discussion will rely mostly on examples from deposits in Alaska and the Sierra Nevada, where U.S.G.S. chemical data are available. Drainage waters from both mine workings and mill tailings in the Sierra Nevada tend to contain similar molar amounts of Ca+Mg and SO_4, as is expected if acid formed from oxidizing pyrite is neutralized by carbonate minerals (R. Ashley, unpub. data).

◆ Mine drainage, several N. Mother Lode mines (Ashley, unpub. data)

■ Argonaut mine, Jackson district, concentrates (Ashley, unpub. data)

▲ Argonaut mine, Jackson district, tailings (Ashley, unpub. data)

▲ Kennedy mine, Jackson district, tailings (Dames & Moore, 1995)

�֎ Lava Cap mine, Nevada City district, tailings (Ashley, unpub. data)

● Harvard mine pit lake, Jamestown district (County of Tuolumne, 1998)

✛ Skyrocket pit lake, Hodson district (Meridian Gold Company, 1997)

▬ North pit lake, Hodson district (Meridian Gold Company, 1997)

Figure 4. pH and arsenic concentrations of mine drainage, drainage from mill tailings and concentrates, and pit lake waters from low-sulfide gold-quartz deposits, Sierra Nevada region, California.

Figure 5. Sulfate and arsenic concentrations of mine drainage, drainage from mill tailings, and pit lake waters from low-sulfide gold-quartz deposits, Sierra Nevada region, California.

Natural drainage: Rivers that drain the gold-mining region of the northern Sierra Nevada and their major tributaries generally show low arsenic concentrations (1 to 3 µg/L), and very low concentrations of other metals where they are not impacted by drainage from VMS deposits (Montoya and Pan, 1992). An exception is Kanaka Creek, a tributary of the North Fork Yuba River that is impacted by numerous gold mines of the Alleghany district, which shows arsenic concentrations of 15 to 25 µg/L. Because the terranes that host low-sulfide gold-quartz deposits in California have been intensively explored beginning 150 years ago, no significant unmined near-surface deposits are known, and consequently there are no data on natural drainage from in-place ore bodies. In Alaska, background concentrations of arsenic in waters are generally

less than 5 μg/L, and waters in contact with undeveloped gold occurrences of this type increase by no more than a few μg/L (Goldfarb and others, 1995).

Mine drainage: Data for mine drainage waters from a dozen sites scattered through the Sierra Nevada region show pH values mostly between 6.0 and 8.0, and arsenic concentrations ranging from 2 μg/L to about 1 mg/L (Montoya and Pan, 1992; Ashley, 1998, 1999; figures 4 and 5). Although there are few data available on arsenic loadings in drainage waters, arsenic values above 100 μg/L are restricted to low-volume discharges (less than 5 to 6 L/sec). Total mercury concentrations range from about 1 to 100 ng/L, and in many cases a relatively large proportion of the mercury is dissolved; methylation rates are mostly in the usual range of 5 percent or less (Ashley, 1999; figs. 6, 7, and 8).

In southeastern Alaska, drainage waters from adits and tailings piles at small- (less than 2 tonnes gold) to medium-sized (2 to 25 tonnes gold) deposits are generally not greatly enriched in dissolved arsenic. Arsenic concentrations locally may reach 100 to 150 μg/L in small discharge volumes from a few mine workings, but these values are rapidly diluted to background levels once they enter larger streams within a few tens of meters of the mine workings (Cieutat and others, 1994; Trainor and others, 1996). Granitoid-hosted veins in the Fairbanks district (Fort Knox deposit) are extremely low in sulfide content, and waters in contact with the ores do not contain more than about 2 μg/L arsenic (R. Goldfarb, unpub. data from Fairbanks Gold Mining Company, Inc.). Drainage from the Independence mine, the largest mine in the Willow Creek district, contains 37 μg/L arsenic, which is attenuated to about one-third that level within 1.5 km downstream (Goldfarb and others, 1997). Discharge from the Alaska-Juneau mine, the largest historic gold mine in Alaska, does not exceed 7 μg/L arsenic and has an average pH of about 8.0 (Goldfarb and others, 1997).

At a small deposit in Virginia, waters in shafts and surface water down-gradient from the shafts all have no more than 1 μg/L arsenic, and pH values range from 5.9 to 6.7 (Seal and others, 1998a, 1998b). These waters, however, show total mercury values at the high end of the range given above, and in the shafts an unusually large proportion of this mercury (as much as about one-third to one-half) is dissolved methylmercury (Seal and others, 1998b). The source of mercury in the waters is suspected to be mercury used for amalgamation at the site.

Tailings drainage: Data for three Sierra Nevada sites (Argonaut, Kennedy, and Lava Cap mines) show that waters which have percolated through mill tailings have pH values between 6.0 and 8.1 (generally above 7.0), arsenic concentrations generally less than 100 μg/L, sulfate concentrations ranging from 3 to 3,000 mg/L, and alkalinity values ranging from 20 to 500 mg/L (Dames & Moore, 1995; Ashley, 1997, 1998, figures 4 and 5). Mercury and methylmercury values are generally the same as for mine drainage, except that water containing suspended tailings particles may have high total mercury levels (as much as 60 μg/L observed; figures 6, 7, and 8). Lost Lake, the remaining impoundment for the Lava Cap mine, Nevada County, California, has pH values of 6.2 to 6.7, arsenic concentrations consistently in the range 90 to 100 μg/L, sulfate concentrations less than 10 μg/L, and iron concentrations around 5 mg/L. Arsenic concentrations in pore waters immediately below the tailings-water interface of Lost Lake range from 1 mg/L to 30 mg/L (Ashley and Ziarkowski, 1999). Arsenic concentrations in the lake cycle seasonally from wintertime lows less than 10 μg/L to summertime highs just over 100 μg/L.
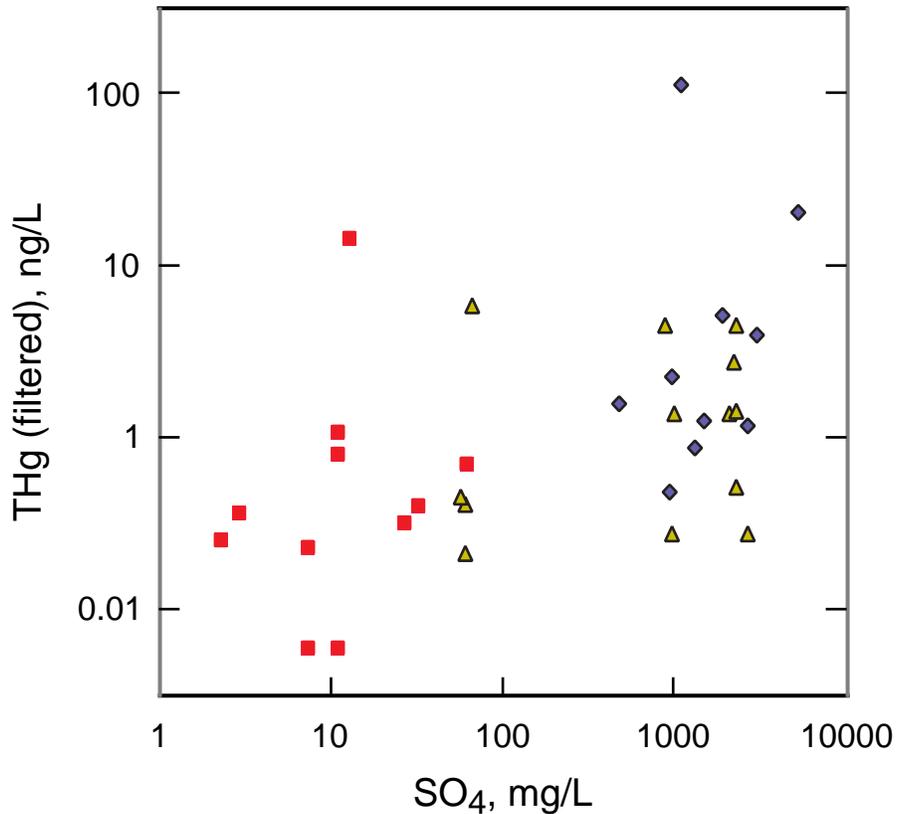
Arsenic concentrations in waters draining gold mine tailings piles in southeastern Alaska and in the Fairbanks district are similar to the concentrations in mine drainage waters described above. In the Fairbanks district, dissolved arsenic levels at the Scrafford mine increased from 5 μg/L to 92 μg/L, and at the Hi-Yu mine from 24 μg/L to 80 μg/L, at sampled sites above and below the associated tailings piles (Goldfarb, 1997).

Sulfide concentrates stockpiled at the Argonaut mine mill tailings site, Amador County, California, produce an acid drainage plume in the wet season. At the head of the plume, pH is 2.5 and metal values are very high, with extreme concentrations of arsenic (more than 100 mg/L; figure 4). Arsenic levels, however, are drastically reduced with increasing pH and continuous iron oxyhydroxide precipitation downstream from the stockpile area. Within 500 m downstream, pH increases to about 5.0 and arsenic is reduced to <2 μg/L owing to adsorption on the iron oxyhydroxides (Ashley and Ziarkowski, 1998; figure 4). Obviously sulfides from these deposits, if concentrated and removed from buffering carbonates, can

have the same impacts as sulfides from any other type of deposit; fortunately abandoned sulfide concentrate stockpiles are rare at historic gold mine sites.
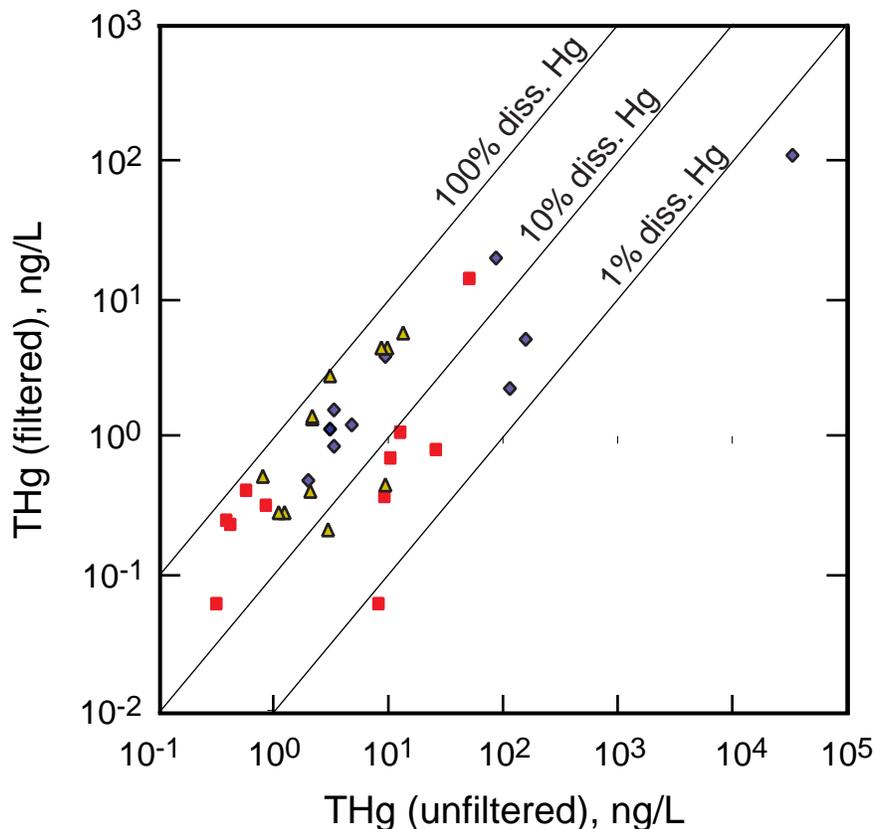
Climatic effects

Because low-sulfide gold-quartz veins are the most common and widespread type of gold deposit world wide, it is no surprise that they occur in almost all climates and ecosystems, from subarctic to humid tropical. In wet climates with abundant water available, impacts on water quality are minimal. In climates with pronounced seasonal wet and dry cycles, such as California, efflorescent salts accumulate in the dry season, store metals in the summer months, and release them at the beginning of the rainy season. Even the relatively benign hydrated magnesium and calcium sulfates associated with these deposits may store some metals (K. Savage, personal communication, 2000). In arid, semi-arid, and seasonally-dry areas these deposits may have significant negative impacts on ground water quality, mainly by increasing sulfate and oxyanion contents, and hardness.

◆ Drainage, Argonaut mine mill tailings (Ashley, unpub. data)

■ Mill tailings impoundment and drainage, Lava Cap mine
   (Ashley & Ziarkowski, 1999; Ashley, unpub. data)

△ Mine drainage, 6 sites in 5 Sierra Nevada districts
   (Ashley, unpub. data)

Figure 6. Sulfate and mercury concentrations of mine drainage and drainage from mill tailings, low-sulfide gold-quartz deposits, Sierra Nevada region, California.

Figure 7. Total dissolved mercury (filtered) vs. total mercury (unfiltered) for mine drainage and drainage from mill tailings, low-sulfide gold-quartz deposits, Sierra Nevada region, California.

Perhaps one of the more important implications of climate relates to stability of stored mill tailings. In wet or even cyclically wet climates, tailings impoundments may remain saturated and largely under reducing conditions. If such impoundments are breached, especially during major storm events, tailings can suddenly be exposed to oxidizing conditions. Under such circumstances at the Lava Cap mine, arsenic and base metals in 60-year-old tailings proved to be easily leached and highly mobile when released and exposed to oxidation in the winter of 1996-1997 (Ashley and Ziarkowski, 1999).

Potential environmental concerns
Human health risks: Surface water contamination associated with low-sulfide gold-quartz deposits does not appear to be a significant problem, as described above, because mine drainage and tailings drainage discharges generally involve relatively small metal loadings. Also arsenic, iron, and other metals are attenuated, and sulfate is usually quickly diluted, within a short distance downstream. Ground water contamination is a potential problem, as demonstrated by the recently-formed pit lakes at two California

189

gold mines, which have arsenic concentrations in the range of 100-1,000 µg/L (see Hydrology section). Wells in hydrothermally altered rocks, where high arsenic concentrations are most likely, are also likely to have relatively high iron and sulfate, which tends to discourage completion and use of wells in potentially arsenic-bearing rocks.

Recent studies have demonstrated that elevated levels of mercury, in dissolved and suspended fractions as well as bedload sediments, exist in the rivers draining the gold-mining region of the Sierra Nevada (Domagalski, 1998), and that mercury becomes available to the aquatic food chain through methylation (Slotton and others, 1997). Analysis of mercury production and use in California, however, indicates that 90 percent or more of the mercury lost to the environment was used in placer operations (mainly hydraulic mines) rather than the lode mines (Churchill, 1999a, 1999b; Hunerlach and others, 1999). Both lode gold mines and placer mines are commonly sources of substantial mercury contamination of soil and water in less-developed parts of the world, owing to inefficient use of mercury in milling (e.g. for barrel amalgamation of coarsely-crushed material) and burning of mercury in open pans for recovery of gold from amalgam (Filho and Maddock, 1997).

- ◆ Drainage, Argonaut mine mill tailings (Ashley, unpub. data)

- ■ Mill tailings impoundment and drainage, Lava Cap mine (Ashley & Ziarkowski, 1999, Ashley, unpub. data)

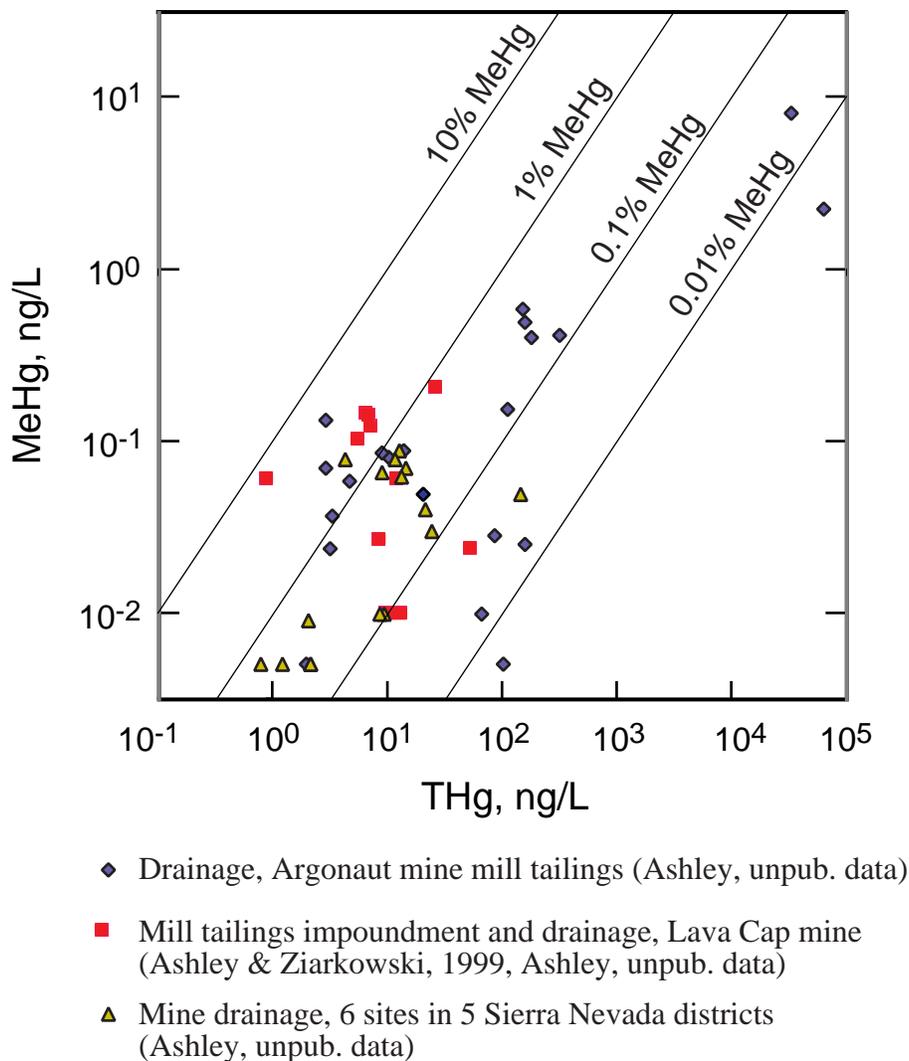- △ Mine drainage, 6 sites in 5 Sierra Nevada districts (Ashley, unpub. data)

Figure 8. Methylmercury vs. total mercury in mine drainage and drainage from mill tailings, low-sulfide gold-quartz deposits, Sierra Nevada region, California.

190

In recent years, concern has risen over exposure to mill tailings in the Sierra Nevada foothills, where housing developments are encroaching on historic mining areas, the main pathways being inhalation of dust and dermal exposure. In the early 1990's concerns over arsenic concentrations at Mesa de Oro, a subdivision built directly on tailings of the Central Eureka mine in Amador County, California, were well publicized (Time Magazine, September 25, 1995), and resulted in a substantial remediation program. Sequential leaching studies and a later in vivo study demonstrated that significant amounts of arsenic in the Mesa de Oro tailings are bioavailable (Walker and others, 1994; Golub and others, 1999). In recent years, the California Environmental Protection Agency has required formal Preliminary Endangerment Assessments of four gold mine tailings sites in the Sierra Nevada, and arsenic has proved to be the only component that consistently exceeds California and USEPA screening levels. Mercury, lead, and cadmium exceed screening levels in some cases, especially the levels for children (California Department of Toxic Substances Control, Site Mitigation Unit, unpub. file reports, 1994-1997).

Ecosystem risks: Aquatic organisms are more sensitive to base metals (copper and zinc) in water than arsenic, so impacts are generally minor because acid drainage and associated high base-metal concentrations rarely occur. Mercury concentrations in water are likely low enough that they are not a problem for organisms at lower trophic levels, but through biomagnification they may be a problem for organisms at higher trophic levels, culminating in the human health concern discussed above.

Based on a biological assessment done shortly after tailings were released at the Lava Cap mine, reduced populations of fish and various insects were reported in the reparian habitat area of the receiving creek, where tailings blanketed the stream terraces. Physical and chemical effects, however, were not separated in this reconnaissance study (State of California Environmental Protection Agency, Department of Toxic Substances Control, 1997).

Physical hazards: As described above, most historic mining of these deposits was done by underground methods. Owing to the tabular geometry of the veins and ore bodies and the tendency of ore shoots to pitch at high angles, vertical workings (shafts and winzes) are almost always present, and unstable glory holes are sometimes present at the surface. Thus, even small gold mines with little or no recorded production may be relatively hazardous.

Further details on physical hazards are available in handbooks by U.S. Bureau of Mines (1994) and State of California Environmental Protection Agency, Department of Toxic Substances Control (1998).

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