

CREEDE, COMSTOCK, AND SADO EPITHERMAL VEIN DEPOSITS (MODELS 25b,c, and d; Mosier and others, 1986a,b, and c)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of veins, stockwork veins, and mineralized breccias associated with intermediate to felsic volcanic centers in areas of regional faulting. Simple and complex sulfide minerals (those that contain arsenic, antimony, or bismuth), gold, electrum, silver, \pm telluride and selenide minerals are important ore constituents. Quartz, carbonate minerals, and adularia (\pm barite, chalcedony, and fluorite) are important gangue minerals. Mineral assemblages in many veins are characterized by well developed lateral and vertical zonation; this zonation may be present within an ore shoot, within a vein or vein system, or within entire districts. Most Creede-type veins are silver-rich, and are dominated by pyrite, sphalerite, galena, and chalcopyrite; variable amounts of carbonate minerals, quartz, and barite are present. Most Comstock-type veins are gold-rich, and are dominated by quartz and adularia \pm carbonate minerals; pyrite, sphalerite, galena, and other sulfide minerals comprise less than several percent of these veins. Sado-type veins are copper-rich equivalents of Comstock-type veins; quartz, adularia, and carbonate minerals are more abundant than chalcopyrite. Wall rock alteration assemblages, including silicic, propylitic, argillic, and advanced argillic assemblages, associated with all three epithermal vein deposit types display well developed lateral and vertical zonation. Intense silicification and pervasive argillic and advanced argillic alteration are common adjacent to shallow parts of veins, wall rock near deep parts of veins is moderately affected by silicification (\pm potassic alteration), and wall rock distal to veins contains propylitic mineral assemblages.

Examples

Creede-type: Creede, Silverton, Bonanza, Colo.; Worlds Fair, Ariz. Comstock-type: Comstock, Nev. Sado-type: Sado, Japan.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include hot-spring Au-Ag (Model 25a); quartz alunite-epithermal (Model 25e); and, if carbonate-bearing rocks are present, polymetallic replacement (Model 19a) deposits.

Potential environmental considerations

- (1) Geoenvironmental signatures associated with different parts of epithermal vein deposits are highly variable on all scales due to well developed spatial zonation within vein and alteration mineral assemblages.
- (2) Pyrite contents of vein ore and carbonate contents of ore and wall rock principally determine the pH and metal content of water draining mines, mine waste piles, and tailings associated with epithermal vein deposits. Veins that contain abundant pyrite and base metal sulfide minerals, relative to carbonate minerals, and veins in rocks with low acid-buffering capacity, such as those affected by silicification and argillic or advanced argillic alteration, have enhanced potential for associated acidic drainage water that contains elevated abundances of dissolved iron, aluminum, manganese, zinc, copper, and lead. Water draining pyrite- and carbonate-rich ore or ore hosted by carbonate-bearing rocks tends to have near-neutral pH but elevated abundances of copper and zinc.
- (3) Historically, gold-rich ore was processed by crushing and mercury amalgamation; soil and stream sediment around historic mining and milling sites may be mercury contaminated. After the late 1800s or early 1900s, amalgamation was less common in ore processing; instead, sulfide-mineral-rich ore was roasted and gold was recovered by cyanidation. After milling, some of this ore was smelted. Soil in areas around roasting or smelting sites may be contaminated by elevated abundances of lead, zinc, copper, arsenic, or antimony.

Mitigation and remediation strategies for potential environmental concerns presented above are described in the section below entitled "Guidelines for mitigation and remediation."

Exploration geophysics

Geophysical expressions of precious-metal epithermal veins and stockworks have been reviewed by Allis (1990), Irvine and Smith (1990), Klein and Bankey (1992), and Watson and Knepper (1994). Silicic and carbonate alteration of volcanic rocks produces reflectance and thermal infrared contrasts and increases their resistivity and density; the extent of associated anomalies can be delineated with detailed gravity, multispectral remote sensing (Arribas and

others, 1989; Collins, 1989), and direct current and electromagnetic (Nishikawa, 1992) surveys, respectively. Gravity anomalies may be complicated by open fractures and brecciated rock, which reduce bulk density. Electrical and gravity anomalies associated with epithermal deposits may be difficult to distinguish from those caused by small intrusions or faults. Resistivity lows and reflectance contrasts associated with argillically altered rock can be delineated by electrical mapping (Bisdorf, 1995) and multispectral remote sensing, respectively. The distribution of clay zones and electrical chargeability associated with sulfide minerals can be mapped with induced polarization. Airborne photography and side-looking radar can identify topographic features that may be related to resistant silicic and carbonate zones and easily-weathered areas affected by argillic alteration. Areas that contain altered magnetite can be outlined by magnetic surveys. Rock affected by potassic alteration can be identified by spectral gamma-ray surveys. Regional gravity, aeromagnetic, and satellite or airborne remote sensing images may help identify linear, circular, and intersecting features associated with calderas and faulted volcanic terranes in which additional detailed surveys are warranted.

References

Geology: Becker (1882), Steven and Ratté (1965), Buchanan (1981), Berger and Eimon (1983), Hayba and others (1985), Heald and others (1987).

Environmental geology and geochemistry: Moran (1974), Plumlee and others (1993), Smith and others (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

The size of most deposits is small (10,000 tonnes) to moderate (several million tonnes). However, a few districts are large to extremely large, including Casapalca, Peru, and Comstock, Nev. (10-20 million tonnes), and Pachuca-Real del Monte (Mexico) (>100 million tonnes).

Host rocks

Epithermal vein deposits are in intermediate to felsic volcanic rocks (andesite, dacite, quartz-latitude, rhyodacite, and rhyolite) and associated volcanoclastic and sedimentary rocks (for example, those deposited in volcanic depressions such as caldera moats).

Surrounding geologic terrane

Most epithermal vein deposits are areas of regional faulting within intermediate to felsic volcanic fields, including volcanoes and caldera complexes from which volcanic rocks that host the deposits were erupted.

Wall-rock alteration

Wall rock alteration assemblages are characterized by strong vertical and lateral zonation between deep, central parts of veins and shallow and (or) distal parts of veins (fig. 1). In many (but not all) districts, host volcanic rocks are altered to propylitic assemblages, including chlorite, epidote, calcite, and pyrite, on a regional or district-wide basis; this type of alteration is distal to most veins. In the central parts of districts alteration varies as a function of depth. At deep levels, the alteration assemblage is characterized by quartz and chlorite \pm some potassic alteration (adularia). At intermediate levels the alteration assemblage consists of quartz; sericite; and illite, which may grade upward and distally to lower-temperature smectite; \pm zeolite minerals. At shallow levels, alteration is characterized by massive silicification, formation of chalcedonic sinter, and pervasive acid-sulfate alteration, including alteration to kaolinite and alunite. In laterally distal parts of districts, rock adjacent to veins may be locally silicified and (or) pyritized. In some places, wall rock along upper parts of veins may be altered to illite, smectite, and alunite or kaolinite.

Nature of ore

Veins and stockwork veins fill fractures in intermediate to felsic volcanic rocks. Veins vary greatly in width, from less than several cm to more than 3 m. Most veins display banded layers characterized by substantial mineralogical differences; the veins can also be quite vuggy and include considerable open space.

Deposit trace element geochemistry

The geochemistry of epithermal veins varies laterally and vertically. Altered wall rock adjacent to veins can have significant enrichments in mineralization-related trace elements (Foley and Ayuso, 1993).

Creede-type: Specific parts of these veins are characterized by elevated abundances of various elemental suites as follows: Deep parts of central veins- Au, Cu, Pb, Zn, \pm Ag, \pm Te, \pm Se. Intermediate parts of central veins- Pb, Zn,

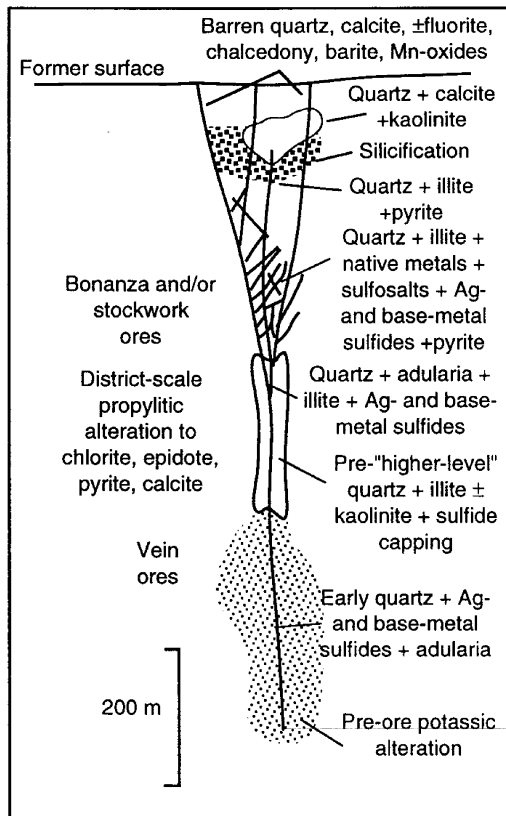


Figure 1. Schematic cross section through an epithermal vein deposit showing distribution of vein and wall rock alteration minerals. Modeled primarily after Creede-type veins; however, with the exception that base metal sulfide minerals are less abundant, the same general zoning patterns are present in Comstock-type vein ore. Figure modified from Mosier and others (1986a) and Berger and Eimon (1983).

Ag, Cu, \pm Mn. Intermediate to shallow parts of central and distal veins- As, Sb, Hg, \pm Au, \pm Mn, \pm Se. Distal, deep parts of veins- Ag, Pb, Zn, \pm Cu, \pm Ba, \pm As, \pm Sb, \pm Mn, \pm Se.

Sado and Comstock-type: Geochemical zonation within most Comstock-type veins is similar to that in Creede-type veins, except that lead and zinc are less abundant throughout all parts of veins.

Ore and gangue mineralogy and zonation

Minerals are listed in approximate decreasing order of abundance. Potentially acid-generating minerals are underlined; those that are acid-generating when oxidized by aqueous ferric iron are denoted by *.

Creede-type veins are base-metal sulfide mineral rich. They contain abundant sphalerite*, galena*, chalcopyrite, and pyrite; lesser amounts of many other sulfide and sulfosalts minerals, such as argentite*, tetrahedrite, pyrargyrite, \pm marcasite, \pm botryoidal pyrite; and variable but generally subordinate amounts of quartz, carbonate minerals (including rhodochrosite, calcite, Mn-siderite), adularia, fluorite, manganese silicate minerals (such as pyroxmangite), barite, and chalcedony.

Comstock- and Sado-type veins are dominated by quartz and adularia and contain variable amounts of carbonate minerals and generally subordinate amounts of sulfide minerals, including pyrite, sphalerite*, galena*, chalcopyrite, and arsenopyrite.

All three vein types tend to be enriched in manganese; abundances of rhodochrosite or manganiferous calcite are moderate to high, and manganese silicate minerals are also abundant. Well developed lateral and vertical vein mineralogy zonation is typical within ore shoots, within veins, and across districts (figs. 1 and 2). This zonation results from variations in the hydrologic and geochemical processes that prevailed during hydrothermal ore genesis.

Mineral characteristics

Textures: Mineral grains can vary from fine to coarse (<1 mm to >10 cm), depending upon the particular district

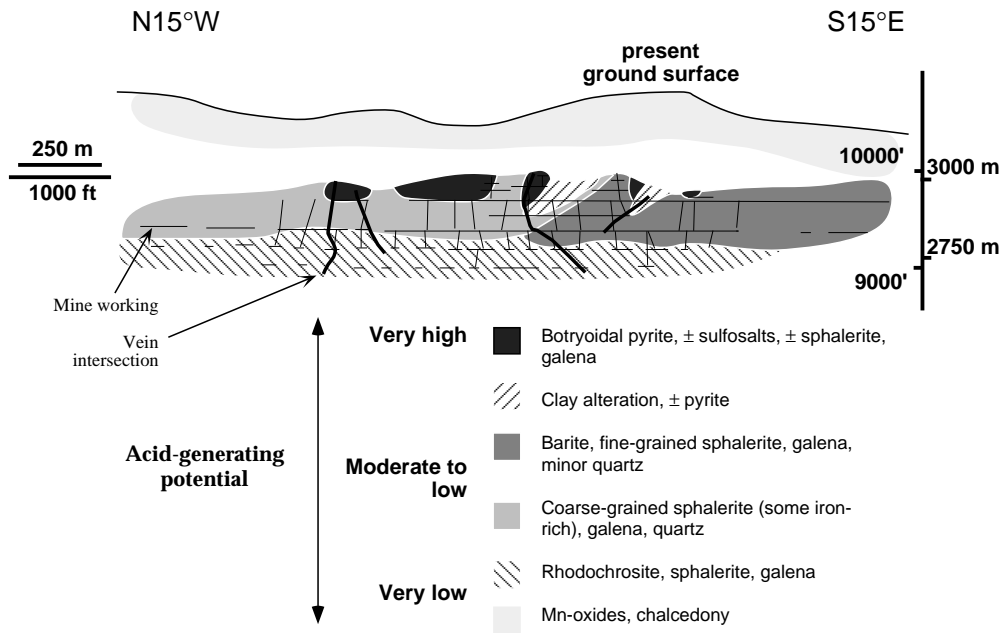


Figure 2. Longitudinal section of the A vein, Bulldog Mountain vein system, Creede district, Colorado, showing lateral and vertical vein mineral zoning patterns. The various mineralogic zones are ranked according to their potential to generate acid drainage water from mine workings or mine waste. A poorly-welded ash-flow tuff occurs immediately above the botryoidal pyrite zone. Fracture permeability in this ash flow tuff is very low, and so the botryoidal pyrite has largely escaped oxidation even though it occurs well above the present water table, which is within the deep rhodochrosite-dominant zone. Ground water that does penetrate beneath the ash flow tuff becomes highly acid, but evaporates, while still in the mine workings, and leaves behind melanterite and goslarite efflorescent salts. Figure modified from Plumlee and Whitehouse-Veaux (1994).

and location within the district. Textures range from euhedral to botryoidal to massive. Crustification sequences are often well developed; bands comprised of one mineral assemblage may be overgrown by one or more successive, mineralogically distinct bands.

Trace element contents: Sphalerite can have low to high iron contents (<1 to >15 mol percent), several tenths to 1 mol percent cadmium, and minor amounts of other trace elements, including silver. Galena can contain silver; <1 mol percent in most cases. Botryoidal pyrite and marcasite can have very high concentrations (as much as 15 weight percent, combined) of arsenic, antimony, silver, mercury, tellurium, selenium, and (or) gold. Carbonate minerals commonly form extensive solid solutions that include manganeseiferous calcite, kutnahorite, and siderite.

General weathering rates: Euhedral to massive, coarse-grained, interlocking sulfide minerals weather at very slow rates; samples of these crystals exposed on mine dumps in cool wet climates for >100 years can still appear fresh and unweathered. Most botryoidal pyrite and marcasite, especially if enriched in arsenic, antimony, and other trace elements, weather very rapidly, in some cases simply by atmospheric water vapor sorption. Rates at which carbonate minerals weather are variable, but increase with decreasing grain size and increasing trace element content. For example, iron-rich calcite and rhodochrosite weather more readily than equivalent minerals with low iron contents. Weathering rates for minerals can be quite high in warm, humid climates.

Secondary mineralogy

Readily soluble minerals underlined. Minerals formed by weathering prior to mining include goethite, jarosite, alunite, halloysite, anglesite, cerussite, smithsonite, manganese-oxide minerals (psilomelane, pyrolusite, braunite), and cerargyrite. Minerals formed by weathering subsequent to mining are primarily soluble sulfate minerals indicative of deposition from locally highly acidic water. Zinc sulfate minerals include goslarite. Iron sulfate minerals noted in published reports include melanterite, although other sulfate minerals, such as copiapite, are also probably present in pyrite-rich ore. Hydrated ferric oxide and iron hydroxysulfate minerals, such as ferrihydrite and schwertmanite, precipitate from acidic to near-neutral mine- and natural- drainage water. Aluminum hydroxysulfate minerals, including basaluminite and jurbanite, precipitate from water having pH between 4.5 and 5.

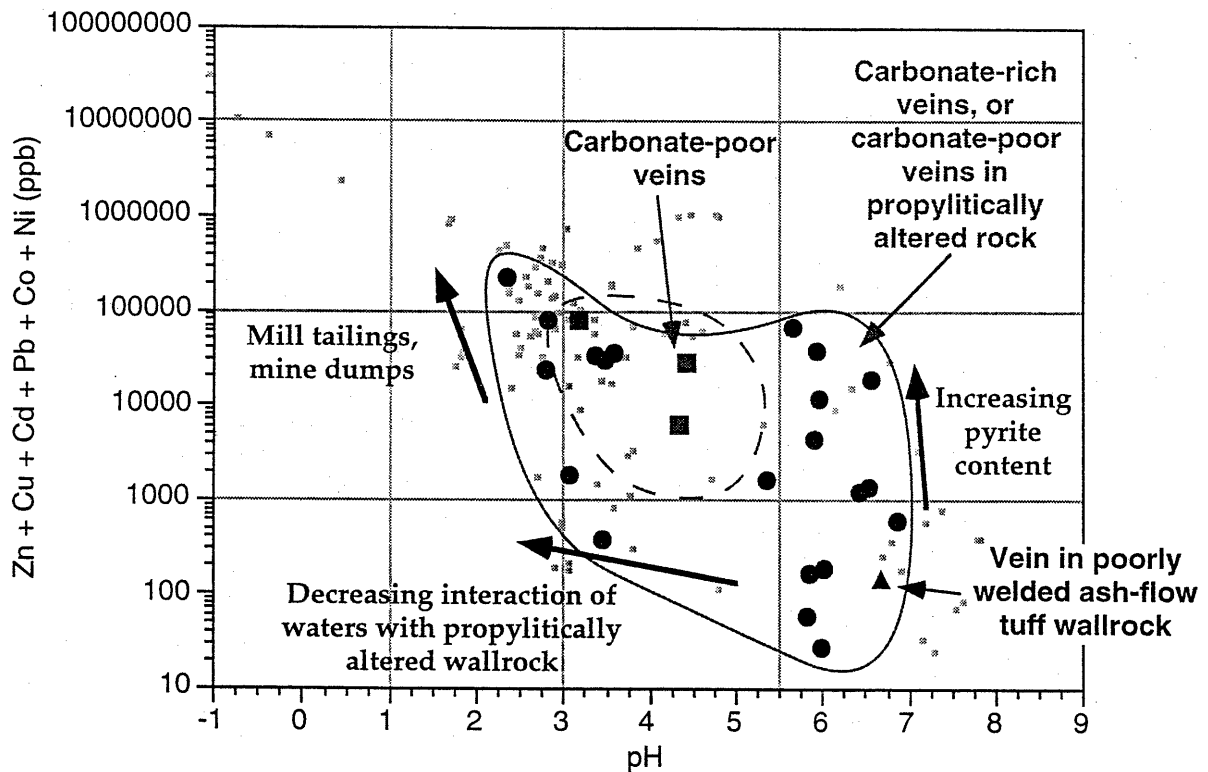


Figure 3. Ficklin plot showing variations in pH and sum of dissolved base metals Zn, Cu, Cd, Co, Ni, and Pb in mine and natural water draining epithermal veins of various geologic characteristics.

Topography, physiography

Silicified zones and quartz-chalcedony veins tend to form topographic highs. Clay altered zones probably erode more rapidly than adjacent less altered rocks, and form topographic lows.

Hydrology

Mine workings provide the most permeability for ground water flow. Faults, joints, and veins, which also focus ground water flow, provide the greatest natural permeability. Flow along unmineralized fractures and vuggy, open-space veins with continuous permeability is greatest; flow along veins completely filled by ore and gangue is minimal. Fracture permeability is also commonly reduced where fractures cross poorly welded ash flow tuffs, and in zones of intense clay alteration; these rocks and altered zones are aquitards or barriers to ground water flow. For example, epithermal ore at Creede is capped by poorly welded tuff that inhibited ascending hydrothermal fluids that formed the deposit and presently inhibits descending oxidized ground water. Most of a zone of botryoidal pyrite that formed directly beneath the cap rock is unoxidized even though it occurs well above the present-day water table; as a result, acid drainage from the botryoidal pyrite zone is very limited, and evaporates prior to exiting mine workings developed in the zone. Zones of hydrothermal brecciation can also be ground water conduits, provided sufficient open space remains; if no open space is present, these breccia zones may impede ground water flow.

Mining and milling methods

Historic: Most epithermal veins were mined in underground tunnels and stopes. However, open pits and glory holes developed in some districts. Mineral processing typically involved milling, gravity separation of coarse precious metals, mercury amalgamation to extract gold and silver, and flotation to extract lead, zinc, and copper. Sulfide concentrates were smelted in some historic districts.

Modern: Due to the potential for ore dilution by wall rock, vein ore is still largely extracted by underground mining. Deposits in which economic ore is disseminated through large volumes of near-surface rock, such as shallow stockwork vein systems or mineralized sedimentary rocks exposed in caldera moats, can be mined using open pit

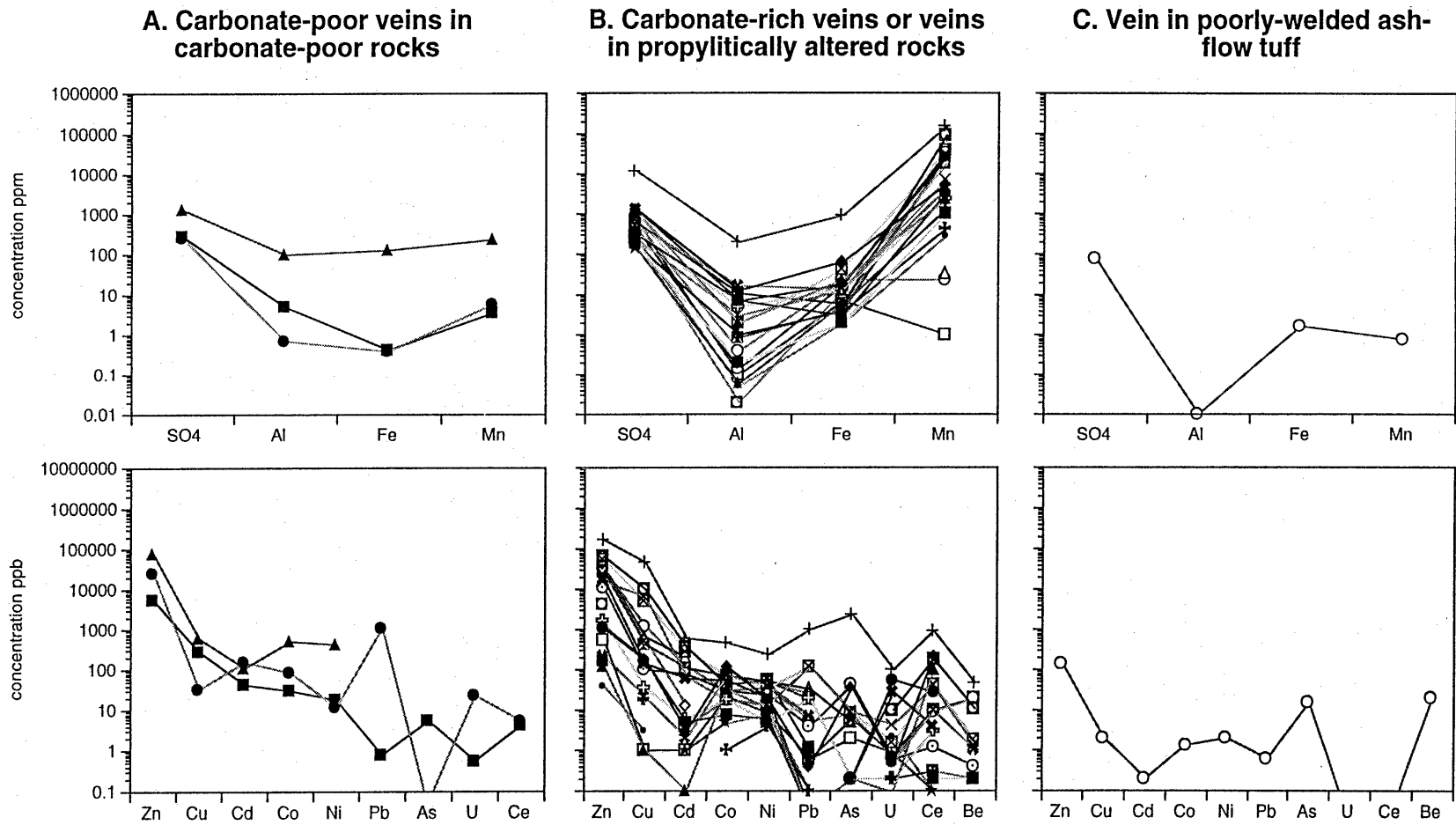


Figure 4. Plots showing concentrations of dissolved constituents in water draining epithermal veins of various geologic characteristics.

techniques. After the late 1800s to early 1900s, processing by amalgamation was increasingly replaced by cyanidation; most sulfide-mineral-rich ore has been roasted prior to cyanidation. Advances in mineral processing technology have recently led to a decline in roasting, however. Most modern processing involves milling, which is followed by cyanidation and extraction of precious metals via carbon-in-pulp or electrowinning. Stopes are backfilled with coarse tailings materials and fine tailings are stored in surface impoundments.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data: Mine drainage data (figs. 3 and 4) pertinent to the Creede, Silverton, and Bonanza, Colo., and Worlds Fair, Ariz., deposits are summarized from Moran (1974), Plumlee and others (1993), Smith and others (1994), and Plumlee and others (in press).

Mine water that drains underground workings in deposits that contain sphalerite, galena, and pyrite in ore with low carbonate mineral contents tends to be acidic, pH ranges from 3 to 5, and contain elevated dissolved metal abundances, including hundreds of mg/l iron, aluminum, and manganese; several to several tens of mg/l zinc and copper; and as much as 1 mg/l lead. Water draining arsenic- and pyrite-rich ore can potentially contain several hundreds of µg/l to several mg/l dissolved arsenic.

Water that drains pyrite-rich tailings and waste dumps can be quite acidic and contain elevated dissolved metal abundances, including thousands of mg/l iron, aluminum, and manganese; tens to hundreds of mg/l zinc and copper; and hundreds of µg/l to several mg/l lead, cadmium, arsenic, and other metals.

Mine water that drains underground workings in carbonate-rich ore, or ore in which water reacts with propylitically altered rock, tends to be near-neutral, pH values range from 5.5 to 7, and contain as much as tens of mg/l dissolved zinc and several mg/l dissolved copper, if ore is pyrite rich.

Mine water that drains underground workings in pyrite-rich veins hosted by propylitically altered rocks can be highly acidic and contain high dissolved metal contents if water flows along veins and does not react with wall rock carbonate minerals. As an example, in 1973, water in the Rawley drainage tunnel, which drains pyrite-sphalerite-galena veins in the Bonanza district, Colo., had a pH near 3.2 and contained high dissolved metal abundances (Moran, 1974). Subsequently, the adit collapsed, which eliminated interaction between ore and atmospheric oxygen and increased interaction between water and carbonate minerals in propylitically altered wall rock. Consequently, the water now has pH values near 6 (Plumlee and others, 1993; Smith and others, 1994) and contains significantly lower dissolved iron and aluminum contents; zinc and copper abundances are essentially unchanged.

Mine water that drains a vein hosted by poorly-welded ash-flow tuff (Creede, Colo.) has a near-neutral pH of 6.7 and contains low dissolved metal contents (Plumlee and others, 1993). The near-neutral pH may result from interaction between water and fine-grained, devitrified glass in poorly welded tuff. Low metals contents may reflect a lack of base metal sulfide minerals in the veins.

Manganese enrichments characteristic of epithermal vein ore cause mine drainage water to have elevated manganese abundances relative to those of iron and aluminum.

Natural-drainage data: Water draining broad areas of propylitically altered rocks can have near-neutral pH and relatively low dissolved abundances of aluminum, lead, arsenic, and copper. This water may have slightly elevated dissolved abundances of some metals, including as much as several mg/l zinc, iron, and manganese. Water draining sulfide-bearing fractures has significantly lower pH and contains correspondingly higher dissolved metal abundances.

Metal mobility from solid mine wastes

Metals and acid are readily liberated from pyrite-rich mine waste and intermittently wet/dry mine workings due to the rapid dissolution of soluble secondary salts. Secondary salt dissolution (and resulting acid and metal generation) is much more rapid than acid consumption by carbonate minerals in dumps or surrounding mine workings. The soluble salts form coatings on mine waste, and fracture fillings in rocks and coatings on mine workings above the water table.

Storm water samples: No data available. However, vegetation kill zones downhill from pyrite-rich mine dumps indicate that highly acidic, metal-rich water can be generated, particularly by secondary salt dissolution, in spite of abundant carbonate-rich rocks on mine dumps.

Soil, sediment signatures prior to mining

Elevated abundances of some metals, including Pb, Mn, Fe, ± Zn, Cu, As, Sb, Hg?, are probably present downslope from vein outcroppings due to mechanical erosion of oxidized vein ore. Elevated abundances of elements

concentrated in oxidized vein ore, including Pb, Mn, Fe, ± Zn, Cu, As, Sb, Hg?, are probably dispersed into nearby stream sediments.

Potential environmental signatures associated with mineral processing:

Historically, gold-rich ore was processed using crushing and mercury amalgamation. Consequently, soil around historic mining and milling sites may be contaminated with mercury. After the late 1800s or early 1900s, processing by amalgamation became less common; sulfide-rich ore was roasted and treated by cyanidation. Roaster particulates may potentially have contaminated soil and sediment in areas surrounding roasting sites with various metals, including lead, zinc, copper, arsenic, antimony, tellurium, and selenium.

Smelter signatures

Sulfide-rich ore was smelted in a number of historic districts. In districts with identified historic smelting activity, soil may contain locally elevated abundances of lead, zinc, copper, ±arsenic, ±antimony, ±selenium, ±tellurium.

Climate effects on environmental signatures

Currently available data mostly pertain to moderately wet, seasonally temperate climatic regimes of the Rocky Mountains; limited data are available for the Worlds Fair, Ariz., district in a relatively hot, dry climate. Mine drainage in the Worlds Fair district has significantly lower pH and higher metal contents than water draining geologically similar veins in a cooler climate at Creede, Colo. Lower pH and higher metal contents may reflect increased evaporation within mine workings, and periodic formation and flushing of soluble salts; however, more data are needed to verify this speculation. No data are available on effects relating to evaporation of near-neutral pH water draining carbonate-rich ore; evaporation of iron-poor water probably causes pH to increase. Mobilization of arsenic, uranium, and possibly selenium (if present in ore) may be enhanced in dry climates if drainage water is alkaline. Climate can strongly affect mineral weathering rates; rates are greatest in warm, humid climates.

Potential environmental effects:

Acid drainage from pyrite- and sulfide-rich veins may adversely affect ground water quality in either wet or dry climates.

(1) The greatest potential for deleterious downstream environmental effects pertain to deposits that consist of pyrite-, sphalerite-, galena-, (±chalcopyrite)-rich ore in carbonate-mineral poor veins; deposits in volcanic terranes minimally affected by propylitic alteration, in which associated water has low acid-buffering capacity; and deposits in which historic mining operations released significant volumes of fine-grained pyritic tailings, which have become part of the sediment column, into rivers or streams. Oxidation of associated tailings can facilitate long-term metal and acid releases, which result in water quality degradation. Downstream effects of acid drainage can be potentially extensive; copper, zinc, manganese, and lesser cadmium can remain mobile for significant distances downstream.

(2) Less significant downstream effects are most likely to be associated with deposits that principally consist of carbonate-bearing vein ore; veins in propylitically altered rock, which tend to have drainage water with near-neutral pH values; and deposits in dry climates, where water evaporates or seeps underground. Zinc and manganese are the principal elements that remain mobile, either in solution or as colloids (Kimball and others, 1995), for the greatest distances downstream. Some arsenic, uranium, selenium, and molybdenum may be mobilized if drainage water is alkaline.

(3) Zones that contain abundant botryoidal pyrite or marcasite have especially high acid drainage generation potential.

(4) Acidic, metal-rich water can develop in pyrite-rich tailings or waste dumps, even if carbonate minerals are present because secondary salt dissolution, and resulting acid and metal generation, is much more rapid than acid consumption by carbonate minerals.

(5) Arsenic and antimony, to a lesser extent, may pose health risks in water draining ore that contains abundant sulfosalt or sulfide minerals that contain elevated abundances of arsenic and antimony; arsenic and antimony abundances are greatest in acid water, but can be moderately high in near-neutral water.

Guidelines for mitigation and remediation:

Careful documentation of district- and mine-scale mineral zoning patterns; rock, soil, and water chemistry; and structural features is important to understand potential variability of environmental signatures.

(1) Acid water can be remediated successfully using lime addition and sodium-bisulfide precipitation of metals; a potentially acid-generating sludge is created. If drainage water is relatively iron-poor, such as most water having near-neutral pH, the amount of particulates formed by liming may be insufficient to effectively sorb all zinc,

cadmium, and nickel. Lime addition to iron-rich drainage water may generate sufficient suspended particulates onto which a major fraction of dissolved arsenic, lead, and copper can sorb, thereby reducing or eliminating need for sodium bisulfide addition; the resulting particulate sludge is non-acid-generating as well. If ore is arsenic-, selenium- or uranium-rich, liming to excessively high pH values may enhance mobility of these elements.

(2) The utility of carbonate-bearing, propylitically altered host rocks in acid drainage mitigation should be considered. For example, acid water could be channeled, away from veins, through these rocks via artificial or natural fractures to help reduce acidity.

(3) Constructed wetlands may be useful in mitigation of less acidic mine water.

(4) Careful mapping of fractures, which focus ground water flow, and poorly welded ash flow tuffs and clay alteration zones, which restrict ground water flow, is essential for an adequate understanding of site hydrology.

(5) Isolation of pyrite-rich waste from weathering and formation of soluble secondary salts is crucial in eliminating storm- and snowmelt-related pulses of acid and metals into surface water. High carbonate mineral content in dump material is not sufficient to prevent acid pulses because soluble secondary salts generate acid and metals much faster than carbonate minerals can consume acid.

(6) In modern milling operations, pyritic parts of mill tailings should be used as underground backfill to prevent accidental release of acid-generating material into downstream sediments.

Geoenvironmental geophysics

Geophysical applications to geoenvironmental investigations are reviewed by King and Pesowski (1993), Watson and Knepper (1994), and Paterson (1995). An example high-resolution airborne multispectral imagery applied to a geoenvironmental investigation is given by King (1995). Highly acidic and (or) metal-enriched ground water is highly conductive and may produce vegetation stress; associated anomalies can be identified by electrical and multispectral imaging methods, respectively. Surface water that contains suspended materials or has high conductivity can also be identified on multispectral imagery. Electrically conductive clay aquitards formed during mineralization or by weathering of ash-flow tuff can be delineated using electromagnetic and induced polarization/resistivity techniques. Distributions of electrically chargeable sulfide minerals can be mapped with induced polarization. Shallow mine workings may be located by electrical, seismic refraction, and gravity surveys, and may be identifiable on infrared thermal imagery. Low-resistivity fluids, whose flow is channeled by brecciated rock, faults, and joints, can be identified by gravity and electrical surveys.

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