AU-AG-TE VEIN DEPOSITS
(MODEL 22b; Cox and Bagby, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits consist of native gold and (or) gold-silver telluride minerals in high-grade quartz veins and (or) low-grade, near surface disseminated native gold and pyrite (with or without telluride minerals) in permeable host rocks. Porphyritic alkaline igneous rocks, many of which display explosive-magmatic features (diatremes, breccia pipes, or stockworks), are spatially and perhaps genetically associated with the deposits. Veins are localized along fracture zones; some veins are concentrated at intersections of crosscutting structural features. Disseminated deposits are commonly adjacent to major structures. Although wall-rock alteration associated with veins is restricted (fig. 1), alteration associated with disseminated deposits may be widespread within or near igneous centers.

Examples

Vein-type deposits: Cripple Creek, La Plata, Boulder County, and Rosita, Colo.; Horn Silver, Silver Queen, Sulphurets Camp, British Columbia, Canada; Judith Mountains (Warm Springs, Spotted Horse), Little Rocky Mountains (Zortman-Landusky), Golden Sunlight, Mont.; northern Black Hills (Annie Creek, Foley Ridge, and Richmond Hill), S. Dak.; White Oaks and Ortiz, N. Mex.; Emperor, Fiji; Musariu, Sacaramb, Romania.
Disseminated deposits: Cripple Creek, Colo.; Zortman-Landusky, Golden Sunlight, Mont.; Ortiz, N. Mex.; northern Black Hills, S. Dak.; Ladolam, Lahir Island; Porgera, Papua New Guinea.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include alkaline porphyry copper (Model 17), porphyry gold-copper (Model 20c), polymetallic veins (Model 22c), polymetallic replacement (Model 19a), placer gold (Model 39a), distal disseminated silver-gold (Model 19c; Cox, 1992).

Potential environmental considerations

(1) Vein deposits are mined dominantly by underground operations; vein clusters are mined in open-pits. Low-grade disseminated deposits are mined by open-pit operations. Most of these mining activities involve rocks with relatively low sulfur (in sulfide minerals) and high tellurium contents. Abundant carbonate minerals in alteration and gangue assemblages (and high CO_2 contents currently venting in some underground mines, for example Cripple Creek, Colo.) associated with these deposits create high acid-buffering capacity.
(2) Water draining these deposits has low metal contents because pH is neutral to near-neutral. In areas underlain by rocks with low acid-buffering capacity, water draining open-pit mines may have elevated concentrations of iron, arsenic, copper, manganese, and zinc.
(3) Soluble secondary minerals, including sulfate minerals, could cause short-term pulses of acidic, metal-bearing water from mine sites.

Exploration geophysics

Aeromagnetic and gravity studies (Kleinkopf and others, 1970) at Cripple Creek, Colo., show that geophysical anomalies are correlated with alteration intensity. Distribution of pyrite and clay in altered rock can be studied using induced polarization/resistivity. Brecciation, fracturing, and faulting associated with volcanic centers create pathways for pore water, oxidation of magnetite, and alteration of primary minerals to clay. Rock in these areas has low density, magnetization, and resistivity that can be identified by gravity, magnetic, and electromagnetic or direct current resistivity surveys. Potassic alteration and uranium and thorium in alkalic igneous rocks can be mapped by gamma-ray spectrometry. Aerial gamma-ray surveys (Pitkin and Long, 1977) identify anomalous potassium radiation associated with deposits at Cripple Creek, Colo. Alteration assemblages may be identified with multispectral remote sensing. Taranik (1990) successfully mapped the distribution of supergene iron oxide minerals using this technique. In addition, Livo (1994) characterized the distribution and nature of hydrothermal alteration using remote sensing techniques.

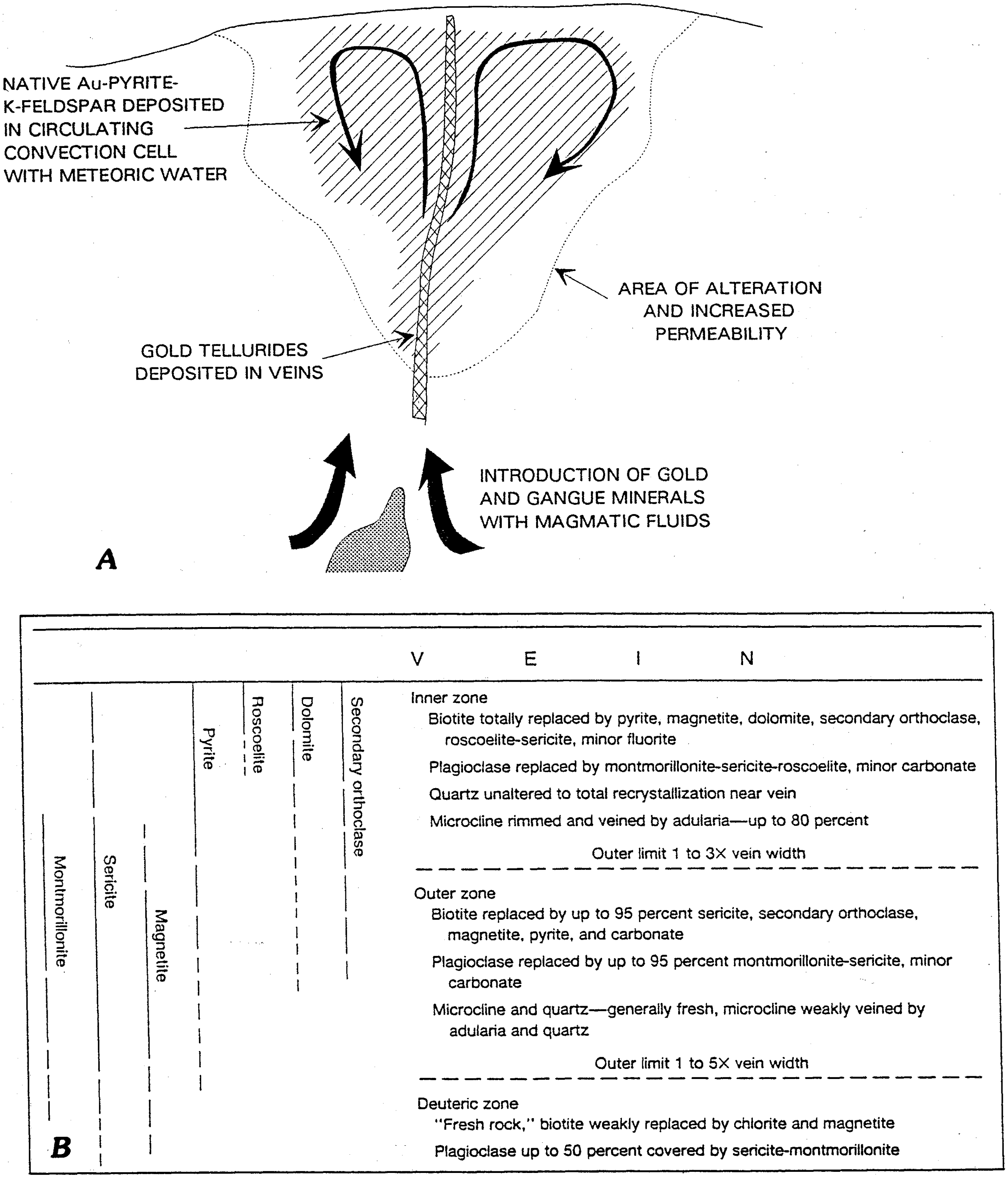

Figure 1. *A*, Conceptual model for a Au-Te system (based on Cripple Creek, Colo.; Pontius, 1992). Native gold and pyrite-rich disseminated deposits may be lateral or upper level equivalents to vein deposits. *B*, Vein-related wall-rock alteration (Thompson and others, 1985).

<u>References</u>

Kelly and Goddard (1969), Witkind (1973), Giles (1983), Mutschler and others (1985), Porter and Ripley (1985), Thompson and others (1985), Kay (1986), Saunders (1986), Ahmad and others (1987), Birmingham (1987), Afifi and others (1988), Saunders (1991), Pontius (1992), and Mutschler and Mooney (1995).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Typically 1-2 Mt (0.3-0.6 oz per ton) for vein deposits. Cripple Creek, Colo., one of the World's largest gold-telluride vein systems, has produced 41 Mt (average, 0.5 oz per ton); disseminated bulk minable deposits range from 32 Mt (0.037 oz per ton) at Cripple Creek to 66 mt (0.03 oz per ton) at Zortman-Landusky, Mont.

Host rocks

Most gold-silver-tellurium deposits are hosted in alkalic, silica-undersaturated rocks such as syenite, monzonite, diorite, phonolite, monchiquite, or vogesite; less common host rocks include silica-undersaturated low-titanium basalt (shoshonite). Except for calcic plagioclase, these rocks contain minerals with minimal acid buffering capacity.

Surrounding geologic terrane

Most gold-silver-tellurium deposits are associated with the late phases of orogenesis or failed rifting events; most deposits in the United States are along the eastern edge of the area affected by Laramide deformation and are in terranes composed of a variety of rock types, including metasedimentary, metavolcanic, carbonate, and volcanic rocks of diverse ages.

Wall-rock alteration

Alteration results from pre-ore igneous activity, vein-type mineralization, or disseminated gold and pyrite mineralization.

Igneous-related alteration: Argillization and dolomitization are characterized by weak to moderate clay alteration, sericitization, and minor recementing by dolomite; this type of alteration creates broad zones of increased permeability along major structures.

Vein-type deposits (fig. 1): Alteration is most extensively developed along vein junctions. Inner zone primarily consists of dolomite, adularia, sericite, roscoelite, and pyrite. Outer zone primarily consists of montmorillonite, sericite, adularia, magnetite, pyrite, and carbonate; this zone is typically 1 to 5 times (Cripple Creek, Colo.) vein width but locally extends as much as 20 times vein width (Boulder County).

Disseminated deposits: Potassium feldspar-pyrite alteration is characterized by pervasive flooding of fine-grained sanidine, orthoclase, and adularia along with moderate to strong sericitization and fine- to medium-grained pyrite. This alteration is most prominent in the broad vuggy permeable zones within 300 m of the surface. Strong potassium feldspar alteration creates a hardened porcelainous rock that resembles jasperoid.

Nature of ore

Vein deposits are usually high-grade but may be small and erratically distributed. Nearly all gold production from these deposits is from gold- and gold-silver telluride minerals. Base metals are infrequently present and are volumetrically minor. Most veins are structurally-controlled. Some structural zones display extensive vertical continuity; mineralized rock, with little evidence of mineralogic zoning or grade variation, can extend to depths of 1,000 m or more (Cripple Creek, Colo.). Lower-grade disseminated deposits containing native gold and auriferous pyrite may also be confined to structural intersections or major shear zones. Lower-grade deposits are best developed in permeable wall rocks, mostly igneous rocks or vent breccias, within 300 m of the surface.

Deposit trace element geochemistry

Trace element geochemical signatures depend on telluride mineralogy, but primary enrichments include Ag, As, Au, Ba, Bi, Cu, F, Fe, Hg, Mo, Mn, Ni, Pb, Sb, Te, V, and Zn. Both types of deposits appear to have had abundant CO_2 distributed throughout their vertical extent; deeper workings (Cripple Creek, Colo.) currently vent extensive amounts of CO_2 along major veins. These deposits are characterized by relatively low sulfur (in sulfide minerals) abundances, and usually by Au>Ag.

Ore and gangue mineralogy and zonation

Vein-type deposits: Ore minerals include gold-silver telluride minerals (calaverite, sylvanite), native gold and (or) native tellurium, and other telluride minerals (most commonly krennerite, petzite, hessite, coloradoite, melonite, altaite, tetradymite). Deposits also contain variable amounts of common base metal sulfide and sulfosalt minerals (pyrite, chalcopyrite, sphalerite, galena, and tetrahedrite); some deposits contain cinnabar. Gangue minerals include adularia, chlorite, fluorite, sericite, roscoelite, magnetite, hematite, barite, celestite, and carbonate minerals. The

generalized paragenesis includes early base-metal sulfide minerals, followed by telluride minerals (with or without native tellurium), hypogene native gold, and late-stage cinnabar. Quartz, fluorite, and pyrite are present throughout the sequence.
Disseminated deposits: Ore minerals are native gold, auriferous pyrite (as much as 2-3 percent), and occasionally telluride minerals (sylvanite, Zortman-Landusky, Mont.), although telluride minerals are often absent (Cripple Creek, Colo.). Gangue minerals include quartz, adularia, and fluorite.

Mineral characteristics
Carbonate minerals and quartz are dominant in banded, symmetrical veins. Ore minerals form groups of blades or small masses and locally, open-space fillings in vugs. In veins, complex intergrowths of several telluride minerals are common. In some case, minerals are so complexly intergrown that they cannot be easily identified. Breccia-filling textures are common in some deposits. Vein ore ranges from fine grained (0.01 to 1.5 mm) to coarse-grained, bladed crystals (0.5 to 2 cm). Low-grade disseminated deposits consist of microcrystalline native gold and pyrite disseminated in permeable host rocks.

Secondary mineralogy
Telluride minerals are easily destroyed by weathering. Some tellurium is redeposited as green oxide minerals (emmonsite). Native gold is deposited during supergene enrichment of some deposits. Late hydrothermal activity and oxidation of some deposits extends to depths of 30 to 180 m (Cripple Creek, Colo.; Zortman-Landusky, Mont.) and in others to depths of only 1.5 to 15 m (Boulder, Colo.). The depth of oxidation generally depends on the openness and permeability of vein structures. Late hydrothermal activity deposits a variety of sulfate minerals along with jarosite, anhydrite, opal, and chalcedony. A variety of iron (limonite) and manganese oxide minerals results from oxidation. Dolomite formed during early igneous-related activity and present within the oxidized zone may be leached during oxidation. Gott and others (1969) found that secondary geochemical dispersion results in anomalies of gold, silver, and tellurium, accompanied by enrichments of iron, lead, mercury, antimony, arsenic, and vanadium. A manganese-enriched outer halo is present commonly.

Topography, physiography
Alkaline intrusive and associated volcanic rocks commonly form topographic highs. However, if igneous-activity-related alteration, including argillization and dolomitization, is prevalent, broad high permeability zones, which are highly susceptible to increased erosion, may result. Alteration related to vein type mineralization is restricted in spatial extent and probably does not contribute to enhanced erosion.

Hydrology
Since these deposits are commonly structurally controlled, ground water flow is focused along high permeability structures. Numerous historic underground workings, typical of some districts, also control water recharge and discharge. Pre-mining ground water oxidizes rock to significant depths, for instance, 180 m at Cripple Creek. Contacts between igneous rocks and surrounding wall rock constitute significant ground water conduits. Since deposits are typically located at topographic highs associated with volcanic rocks, surface water flows radially away in all directions.

Mining and milling methods
Historic: Most historic operations involved underground workings along veins. Ore was processed by stamp mills, followed by mercury amalgamation or cyanide vat leaching. The second largest cyanide mill in the world was at one time located in Ruby Gulch (near the current Zortman-Landusky, Mont., mine).
Modern: Most modern operations are open-pit mines that exploit vein clusters or disseminated gold along major structures. Ore is processed primarily by cyanide heap leaching.

ENVIRONMENTAL SIGNATURES
Drainage signatures
Natural drainage water: The only data concerning the geochemistry of natural water draining gold-silver-telluride veins are those for the Zortman-Landusky, Mont., deposit; data are part of environmental impact studies (Scott Haight, U.S. Bureau of Land Management office, Lewistown, Mont., oral commun., 1995; Zortman-Landusky area Environmental Impact Statement, 1995). Pre-mining (pre-1979) data from the Zortman-Landusky area indicate the

following:
(1) Surface water was slightly acidic to slightly alkaline (pH 6.9 to 8.4) and contained low dissolved constituent concentrations, including 8 to 134 mg/l sulfate, 0.002 to 0.01 mg/l arsenic, 0.011 to 0.17 mg/l iron, and 0.01 mg/l zinc.
(2) Groundwater was slightly acidic to slightly alkaline (pH 6.5 to 8.0) and contained low to moderate dissolved constituent concentrations, including 2 to 186 mg/l sulfate, 0.005 to 0.31 mg/l arsenic, 0.021 to 11 mg/l iron, and 0.005 to 0.88 mg/l zinc. Relatively higher concentrations of sulfate and metals in some water samples are due to the presence of shale, which has naturally high concentrations of sulfate and metals, in some drainage areas.
(3) Elevated concentrations of arsenic in some groundwater indicates that alluvial groundwater had been affected by historic, those conducted prior to open pit mining, mining activities.
Mine drainage water: Most mine water is neutral (pH 7 to 8), but slightly acidic water (pH 6.0 to 6.9) has been reported near the Zortman-Landusky, Mont., mine (U.S. Environmental Protection Agency, 1990). Most water draining from mines has low concentrations of total dissolved metals (Zn+Cu+Cd+Co+Ni+Pb <100 µg/l) (Plumlee and others, 1993) but may have elevated concentrations of zinc (U.S. Environmental Protection Agency, 1990; Keffelew, 1995). Other metals, including iron, arsenic, copper, and manganese rarely are present in high concentrations but may be present at abundances that exceed Federal Secondary Drinking Water Standards (U.S. Environmental Protection Agency, 1990). At Cripple Creek, Colo., extensive areas of dolomitized rock, mostly at deep levels, and CO_2, that is currently outgassing, buffer acidic solutions (Jeff Pontius, Pikes Peak Mining Company, oral and written commun., 1995). At Zortman-Landusky, surrounding carbonate rocks quickly buffer slightly acidic water (U.S. Environmental Protection Agency, 1990).
Potentially economically recoverable elements: Scandium abundances in Cripple Creek, Colo., mine drainage are relatively high and may represent an economically recoverable commodity (Geoff Plumlee, oral commun., 1995).

Metal mobility from solid mine wastes
Metal mobility away from gold-tellurium deposits may be limited if abundant carbonate rock, alteration assemblages, and (or) gangue minerals are associated with deposits. Water quality data from wells and springs in the Zortman-Landusky, Mont., area show that ground water in the area is hard to very hard, alkaline (pH 7 to 7.5), and of the calcium carbonate type. Surface water from a stream draining the waste and heap leach area is slightly acidic (pH 6 to 6.9) and contains as much as 297 µg/l arsenic and 36 µg/l cyanide (U.S. Environmental Protection Agency, 1990). Flow and water quality vary slightly with seasonal precipitation rates. During spring runoff, one stream contained elevated manganese abundances (U.S. Environmental Protection Agency, 1990).

Soil, sediment signatures prior to mining
Because most gold-tellurium deposits in the United States have been mined by underground and (or) placer mining methods since the late 1800s, including for instance, Boulder County and Cripple Creek, Colo., and Zortman-Landusky, Mont., pre-mining geochemical data for soil and sediment associated with these deposits are rare. However, data obtained in 1978, before initiation of open-pit mining and heap leaching operations, as part of the National Uranium Resource Evaluation program, are available for the Zortman-Landusky, Mont., area. Stream sediment samples collected from streams within 5 km of and draining mineralized areas contain <5 to 12 ppm silver, 0.04 to 0.4 ppm gold, <5ppm cadmium, 18 to 81 ppm copper, 1.4 to 4.2 weight percent iron, 200 to 2,020 ppm manganese, 7 to 197 ppm lead, and 70 to 1,131 ppm zinc (Shannon, 1980).

Potential environmental concerns associated with mineral processing
Mercury amalgamation of ore during historic operations may represent a source of mercury contamination not directly associated with these mineral deposits.

Historic cyanide milling operations at Zortman-Landusky, Mont., discharged waste water to watercourses (U.S. Environmental Protection Agency, 1990). Most modern heap leach operations rinse heap-leach residues, barren ore, remaining after the leaching cycle with fresh water to remove residual cyanide. Residues are left on heap leach pads. Heap leach and other cyanide processing solutions are most likely to include gold and silver cyanide complexes with lesser arsenic, antimony, nickel, vanadium, and iron present as weak cyanide complexes.

Smelter signatures
No data currently available.

Climate effects on environmental signatures

The effects of various climate regimes on the geoenvironmental signature specific to gold-silver-tellurium deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Acid- or metal-bearing water resulting from pyrite oxidation has low resistivity and consequently can be identified with electromagnetic or direct current induced polarization/resistivity surveys and ground penetrating radar. Structural and stratigraphic features such as faults, bedrock topography, buried channels, and aquitards that affect water flow away from mine areas may be studied using electromagnetic or direct current resistivity, seismic refraction or reflection, magnetic, gravity, and ground penetrating radar surveys; water flow may be monitored using self potential methods. The distribution of supergene iron oxide and sulfate minerals, especially jarosite, as well as primary hematite may be identified using remote sensing techniques.

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