

CLIMAX MO DEPOSITS (MODEL 16; Ludington, 1986)

by Steve Ludington, Arthur A. Bookstrom, Robert J. Kamilli, Bruce M. Walker, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits are large (100 to 1,000 million metric tons of ore containing 0.06 to about 1 weight percent molybdenum) and consist of stockworks of molybdenite-bearing veins and veinlets, within larger masses of hydrothermally-altered rock. Orebodies are in and above the apices and on the apical flanks of small metaluminous porphyry stocks of the high-silica (>75 weight percent SiO₂) rhyolite-alkalic suite of Carten and others (1993). Orebodies mimic the shape of and surround the top of their subjacent stocks. Multiple intrusions and overlapping ore shells are characteristic of productive systems; at Henderson, Colo., at least eleven intrusions are associated with mineralization processes. Individual ore shells, which coincide with orthoclase-bearing zones of altered rock, are commonly underlain by highly silicified rock and (or) by characteristic zones of layered unidirectional solidification features (USTs) or *stockscheider*; these zones consist of crenulate layers of quartz + fluorite or other minerals that are separated by layers of aplite and aplite porphyry. These layers parallel contacts between stocks; crystals terminate inward from these contacts.

Climax molybdenum deposits exhibit distinctive zoned alteration patterns. Early silicic alteration, along with surrounding potassic alteration (K-feldspar replaces plagioclase) of porphyry and wall rock characterize the inner zone. Above each ore shell is a much larger, lower temperature, phyllic zone, that consists of stockworks of veinlets that contain quartz, pyrite, and (or) sericite, and (or) illite, and (or) topaz, with phyllic envelopes, some of which may contain tungsten (wolframite) and tin (cassiterite). The entire molybdenum system commonly is surrounded by a very large zone of propylitic alteration, in which iron- and magnesium-bearing minerals are converted to various combinations of chlorite, albite, calcite, and epidote. At Silver Creek (Rico), Colo., this zone extends nearly 2 km above the molybdenum deposit (Larson and others, 1994). Shale-hosted deposits may be surrounded by a large zone of biotite hornfels. All alteration assemblages display anomalously high amounts of fluorine, which is contained in fluorite, topaz, and micas; the deposits share many characteristics with greisens.

Examples

Climax (Wallace and others, 1968), Henderson (Carten and others, 1988), Urad, Mount Emmons, Winfield, Middle Mountain, Silver Creek (Rico), and Redwell Basin, all in Colo.; Questa, N. Mex.; Pine Grove, Utah (Keith and others, 1986); Mount Hope, Nev. (Westra and Riedell, 1995).

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include minor, silver-rich, polymetallic vein (Models 22c) and polymetallic replacement deposits (Models 19a) that appear to be concentric and distal to some deposits. Veins commonly contain quartz, fluorite, rhodochrosite, base-metal sulfide minerals, and tetrahedrite. These base-metal systems may be more extensive in some environments, as at Silver Creek (Rico) (Larson, 1987), and Crested Butte (Sharp, 1978).

Climax deposits, possibly underlain by molybdenum greisen deposits (Kotlyar and others, 1995), are genetically related to molybdenum, tin, and tungsten greisen systems. Burt and others (1982) have suggested that rhyolite-hosted tin deposits may also be underlain by Climax type deposits.

Potential environmental considerations

Oxidation of pyrite in large, unmined deposits, such as Winfield, Colo. (Ranta, 1974), may contribute significant acidic drainage to nearby streams. Mining and milling of large tonnages of sulfide-mineral-bearing stockwork ore may exacerbate acid drainage problems, although most pyrite is outside orebodies. Tailings may contain finely-ground pyrite-bearing rock that, when oxidized, may generate large quantities of acid. This acid, if not artificially neutralized, may be partially neutralized as streams traverse plagioclase- or carbonate mineral-bearing bedrock. Most other minerals and elements present in these deposits are relatively non-toxic.

Molybdenite differs from most sulfide minerals in that it releases molybdenum as an anion, not a cation, during weathering. Geochemical mobility of most metallic cations increases with acidity, whereas mobility of molybdate anions increases with alkalinity. The molybdate ion, which is stable at low pH, is geochemically

immobile, because it is strongly coprecipitated with and (or) adsorbed on ferric oxyhydroxide at low pH. Plants growing in soil with a pH of 5.5 or less commonly contain only trace amounts of molybdenum, whereas plants growing in soil with a pH of 6.5 or higher are commonly enriched in molybdenum (Hansuld, 1966).

Molybdenosis is a disease that affects ruminants that graze on molybdenum-rich vegetation that grows on alkaline soil in which the ratio of bioavailable copper to bioavailable molybdenum (as molybdate) is less than 2:1. Thus, molybdenosis is more related to climatic factors, soil alkalinity, and the relative bioavailability of copper and molybdenum, than to point sources of molybdenum.

High fluorine concentrations associated with Climax deposits may be beneficial. Children who grew up at Climax, Colo., had brown-speckled, but cavity-free teeth, due to the high fluoride content of local drinking water.

Uranium concentrations are anomalously high in Climax molybdenum systems. Granitic rocks associated with the deposits contain uranium-bearing accessory minerals, most of which are not recovered but deposited with mill tailings; uranium abundances in Ten Mile Creek, which receives input from Climax tailings ponds, are significantly elevated, however. Distal veins peripheral to Climax deposits, commonly several kilometers distant, may also have anomalously high uranium contents. Thus, radon gas in the mines is a potential hazard; radon abundances must be monitored and mitigated by proper ventilation, as necessary.

Exploration geophysics

Alteration associated with shallow or exposed deposits produce diagnostic color (reflectance) patterns on remote-sensing images. Pyrite and hydrothermal clays in the phyllic alteration zone display reduced resistivity and high induced potential anomalies (Fritz, 1979). Anomalous uranium, thorium, and potassium abundances can be mapped with airborne gamma-ray spectrometry. Radon in mines or associated with mine-related ground water can be identified using simple detectors. At Mt. Emmons, a magnetic anomaly is coincident with a layer of hydrothermal magnetite below the molybdenite zone (Fritz, 1979; Thomas and Galey, 1982). Local gravity is variable as a function of rock types present in the shallow subsurface; regional gravity lows, produced by multistage, high-silica plutons and underlying granitic batholiths are nearly ubiquitous in association with these deposits. Self potential lows have been reported over phyllic (quartz-sericite-pyrite) alteration zones associated with several deposits (Corry, 1985).

References

Wallace and others (1968), White and others (1981), Carten and others (1988), and Keith and others (1986).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Most deposits are >100 million metric tons, and they may be as large as 1 billion metric tons. Such large deposits may result in special waste storage problems that may impact local geography and stream courses. Hydrothermal alteration may affect an area of many square kilometers, although orebody horizontal cross-sectional areas are usually less than one kilometer.

Host rocks

Deposits are found in crystalline, volcanic, and sedimentary rocks of diverse ages in the western United States.

Surrounding geologic terrane

Surrounding terrane is not diagnostic nor particularly significant with regard to potential environmental impact. Many of these deposits are found in young mountain ranges where mining operations may conflict with scenic and recreational values. Deposits located at high elevations, in the headwaters of drainages, can impact large downstream areas.

Wall-rock alteration

Wall-rock alteration includes (1) high temperature assemblages: quartz + fluorite ± molybdenite, quartz + K-feldspar + fluorite ± molybdenite, and quartz alone, all found near the center of the hydrothermal system; (2) moderate temperature assemblages: quartz + K-feldspar + magnetite + brown biotite ± topaz ± fluorite, and quartz + sericite + green biotite ± topaz ± fluorite; and (3) low temperature assemblages: pyrite + sphalerite + garnet + rhodocrosite + clay, and a large propylitic zone (albite + epidote + chlorite) that may extend kilometers beyond intrusive centers. Pyrite, a constituent of moderate- and low-temperature assemblages, is the most significant mineral with regard to environmental concerns. Rocks from the quartz-sericite-pyrite zone at Climax, Colo., contain about 2 to 10 volume percent (4 to 20 weight percent) pyrite.

Nature of ore

Orebodies are typically overlapping, inverted, and saucer-shaped, and are stacked above one another, with or without offset. High grade parts of composite orebodies form where individual orebodies associated with discrete stocks overlap. Assay walls of orebodies are typically quite sharp.

Molybdenite is present primarily with high-temperature alteration assemblages, both as a vein-filling phase and as replacements in vein selvages. Pyrite is rarely present with molybdenite, but rather is found in later, lower-temperature veins and assemblages that cut earlier molybdenite veins. Late, insignificant sphalerite- and galena-bearing veins may cut pyrite veins in distal parts of systems.

Climax molybdenum deposits are relatively barren of other metals, except tin and tungsten, each of which may form weakly enriched zones in the outer parts or outside molybdenite orebodies. Wolframite was recovered for many years as a by-product of mining at Climax, Colo. Tin is present primarily as cassiterite at Climax, but is in ilmenorutile at Henderson, Colo.

Deposit trace element geochemistry

Source plutons have elevated incompatible element abundances, including 200 to >1,000 ppm rubidium, 1 to >30? ppm cesium, as much as 10 ppm beryllium, 10 to >100 ppm lithium, 25 to >200 ppm niobium, 2 to >20 ppm tantalum, and 0.1 to >1 percent fluorine; most have depleted compatible element abundances, including <100 ppm zirconium, <200 ppm barium, and <100 ppm strontium. Ore-related veins and veinlets contain elevated abundances of other metals, including 4 to >100 ppm uranium, 10 to >50 ppm thorium, 10 to >200 ppm tin, and 2 to >100 ppm tungsten.

Ore and gangue mineralogy and zonation

Primary accessory minerals in ore-related intrusions at Climax, Colo., are zircon, fluorite, topaz, monazite, rutile, brannerite, hematite, and magnetite; mill concentrates also contain ilmenorutile, columbite, uraninite, metamict uranium oxide minerals, xenotime, and euxenite. In addition, ore related intrusions at Henderson, Colo., contain accessory metamict niobium oxide minerals, uranium-bearing thorite, fluorcerite, apatite, and aeschynite (White and others, 1981).

Mineral characteristics

Molybdenite grain size varies widely, from about 0.2 mm in replacement veins to >10 cm in open-space filling. Pyrite is typically fine-grained and is present in alteration selvages.

Secondary mineralogy

In exposed deposits, most pyrite weathers to limonite and other iron oxide minerals, and molybdenite may alter to ferrimolybdate and (or) ilsemannite, $\text{Mo}_3\text{O}_8 \cdot n\text{H}_2\text{O}$; other secondary minerals include jarosite and various clay minerals. In wet areas, some pyrite is totally oxidized causing iron to be dissolved in drainage water; iron subsequently precipitates as hydrous iron oxide.

Where pyrite and molybdenite weather together, weathering products depend on pH, and on the ratio of iron hydroxide to acid molybdate in water draining the area. Ferrimolybdate forms in strongly acidic environments (Hansuld, 1966), molybdenum-bearing jarosite probably forms in moderately acidic environments, molybdenum-bearing iron hydroxide minerals form in weakly acidic to mildly alkaline environments, and geochemically mobile molybdate ion forms in alkaline environments, where $\text{pH} > 6$. Ilsemannite is rare and ephemeral, because conditions for its stability are rarely encountered in the normal weathering environment (Hansuld, 1966).

Weathered deposits commonly exhibit red hematite, yellow jarosite and ferrimolybdate, brown goethite, and peripheral black manganese oxide minerals.

Topography, physiography

Orebodies are high in silica, and may be resistant, but most known deposits are deeply buried. Many known deposits are within or beneath peaks stained a distinctive red color by iron oxide minerals.

Hydrology

Annually variable runoff from winter snowmelt may dramatically affect influx into tailings ponds. Most host rocks have low porosity, but the deposits exhibit high fracture permeability.

Mining and milling methods

These deposits are large, bulk tonnage deposits, and are typically mined by open stope, block caving, and open-pit methods which typically further fracture the rocks, increasing permeability and exposing the deposit and surrounding pyritic rocks to increased flow of oxidizing ground water. Molybdenite is typically concentrated on-site by flotation of finely-ground ore.

ENVIRONMENTAL SIGNATURES

Drainage signatures

A limited amount of information is available for deposits in Colorado. Water draining pyrite-molybdenite zones has a pH of 1 to 3 and contains elevated dissolved metal abundances, including hundreds to thousands of mg/l iron and aluminum, hundreds of mg/l fluoride, tens of mg/l zinc and copper, and 1 to 10 mg/l uranium. Water draining intermediate pyrite shells has a pH of 2 to 5 and contains elevated dissolved metal abundances, including hundreds of mg/l iron and aluminum and <1 to about 10 mg/l zinc and copper. Water draining peripheral base-metal-bearing zones has a pH of about 5.5 and contains elevated dissolved metal abundances, including 1 to 200 mg/l zinc and hundreds of µg/l to several mg/l iron and copper (Plumlee and others, 1995).

Metal mobility from solid mine wastes

Because a significant part of the molybdenite is marketed for use as a lubricant, most ore must be ground very finely in order to liberate resistant phases such as quartz and minor amounts of pyrite. When not below the water table in tailings ponds, this very fine pyrite can oxidize rapidly. Acidic drainage that percolates through and seeps from the toes of tailings is typically collected and recycled to tailings ponds, rather than being released to the environment. Waste dumps may contain several percent pyrite. Post-treatment release of water from tailings ponds can result in large abundances of uranium and fluorine in solution.

Soil, sediment signatures prior to mining

Studies of the region surrounding Henderson, Colo. (Theobald and Thompson, 1959), identified significant concentrations of wolframite, scheelite, and molybdenite in heavy-mineral concentrates from streams that drain the deposit area; metal contents of stream sediment derived from outcrops of the Urad deposit include as much as 3,000 ppm tungsten, 700 ppm molybdenum, 500 ppm tin, 3,000 ppm lead, 50 ppm copper, and 1.5 ppm silver.

Potential environmental concerns associated with mineral processing

Fine-grained silica tailings may become a dust and (or) health hazard. Molybdate ion in solution is a constituent of high-pH flotation mill effluent (Le Gendre and Runnells, 1975). However, as pyrite-bearing tailings weather, pH decreases, and acid molybdate is coprecipitated with and (or) adsorbed on ferric oxyhydroxide. In dry areas, this effect may be offset by the alkalinity of surrounding soil, in which geochemically mobile molybdate ions remains stable. Fine-grained pyrite in tailings is susceptible to rapid oxidation.

Smelter signatures

The lone molybdenum smelter in the United States is in western Pennsylvania; it uses an electrolytic process.

Climate effects on environmental signatures

In areas with higher precipitation, pyrite is more rapidly oxidized but molybdate is more rapidly fixed in iron hydroxide minerals. In most cases the intensity of environmental impact associated with sulfide-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

Sulfide mineral concentrations can be detected by induced polarization surveys. Acid pore water can be identified by low resistivity, and usually by enhanced induced polarization, signatures. Self potential surveys may be used to identify redox centers in tailings; heat from these centers may be identified by infrared surveys or shallow thermal

probes, though numerous interference factors may complicate these investigations. Thickness and structure of tailings may be determined using shallow seismic refraction, electrical, and ground penetrating radar surveys.

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