



Climax-Type Porphyry Molybdenum Deposits

By Steve Ludington and Geoffrey S. Plumlee

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Abbreviations Used in This Report

ppm	part per million
m	meter
mg/L	milligrams per liter
C	Celsius
km	kilometer
km ²	square kilometer
QSP	quartz-sericite-pyrite

Climax-type Porphyry Molybdenum Deposits

Abstract

Climax-type porphyry molybdenum deposits, as defined here, are extremely rare; thirteen deposits are known, all in western North America and ranging in age from Late Cretaceous to mainly Tertiary. They are consistently found in a postsubduction, extensional tectonic setting and are invariably associated with A-type granites that formed after peak activity of a magmatic cycle. The deposits consist of ore shells of quartz-molybdenite stockwork veins that lie above and surrounding the apices of cupola-like, highly evolved, calc-alkaline granite and subvolcanic rhyolite-porphyry bodies. These plutons are invariably enriched in fluorine (commonly >1 percent), rubidium (commonly >500 parts per million), and niobium-tantalum (Nb commonly >50 parts per million). The deposits are relatively high grade (typically 0.1–0.3 percent Mo) and may be very large (typically 100–1,000 million tons). Molybdenum, as MoS₂, is the primary commodity in all known deposits.

The effect on surface-water quality owing to natural influx of water or sediment from a Climax-type mineralized area can extend many kilometers downstream from the mineralized area. Waste piles composed of quartz-silica-pyrite altered rocks will likely produce acidic drainage waters. The potential exists for concentrations of fluorine or rare metals in surface water and groundwater to exceed recommended limits for human consumption near both mined and unmined Climax-type deposits.

Geologic Features

By Steve Ludington

Introduction

Climax-type porphyry molybdenum deposits are extremely rare (this model documents 13 deposits on Earth), especially compared to the hundreds of porphyry copper deposits that exist worldwide. As defined here, the deposits are restricted to the Late Cretaceous and Tertiary and to western North America.

The deposits consist of ore shells of quartz-molybdenite stockwork veins that lie above and surround the apices of cupola-like highly evolved calc-alkaline granite and subvolcanic rhyolite porphyry bodies. These plutons are invariably enriched in fluorine (commonly >1 percent), rubidium (commonly >500 parts per million (ppm)), and niobium-tantalum (Nb commonly >50 ppm). They were formed in an extensional environment in North American continental crust. They formed after peak activity of a magmatic cycle, and most of them are middle to late Cenozoic in age. The location of known deposits, prospects, and related igneous centers is shown in figure 1. Summary papers that form the basis for this model include Wallace and others (1968), Wallace and others (1978), Bookstrom (1981), Mutschler and others (1981), Westra and Keith (1981), White and others (1981), Bookstrom and others (1988), Carten and others (1988), Carten and others (1993), Keith and others (1993), Wallace (1995), and Seedorf and Einaudi (2004a,b).

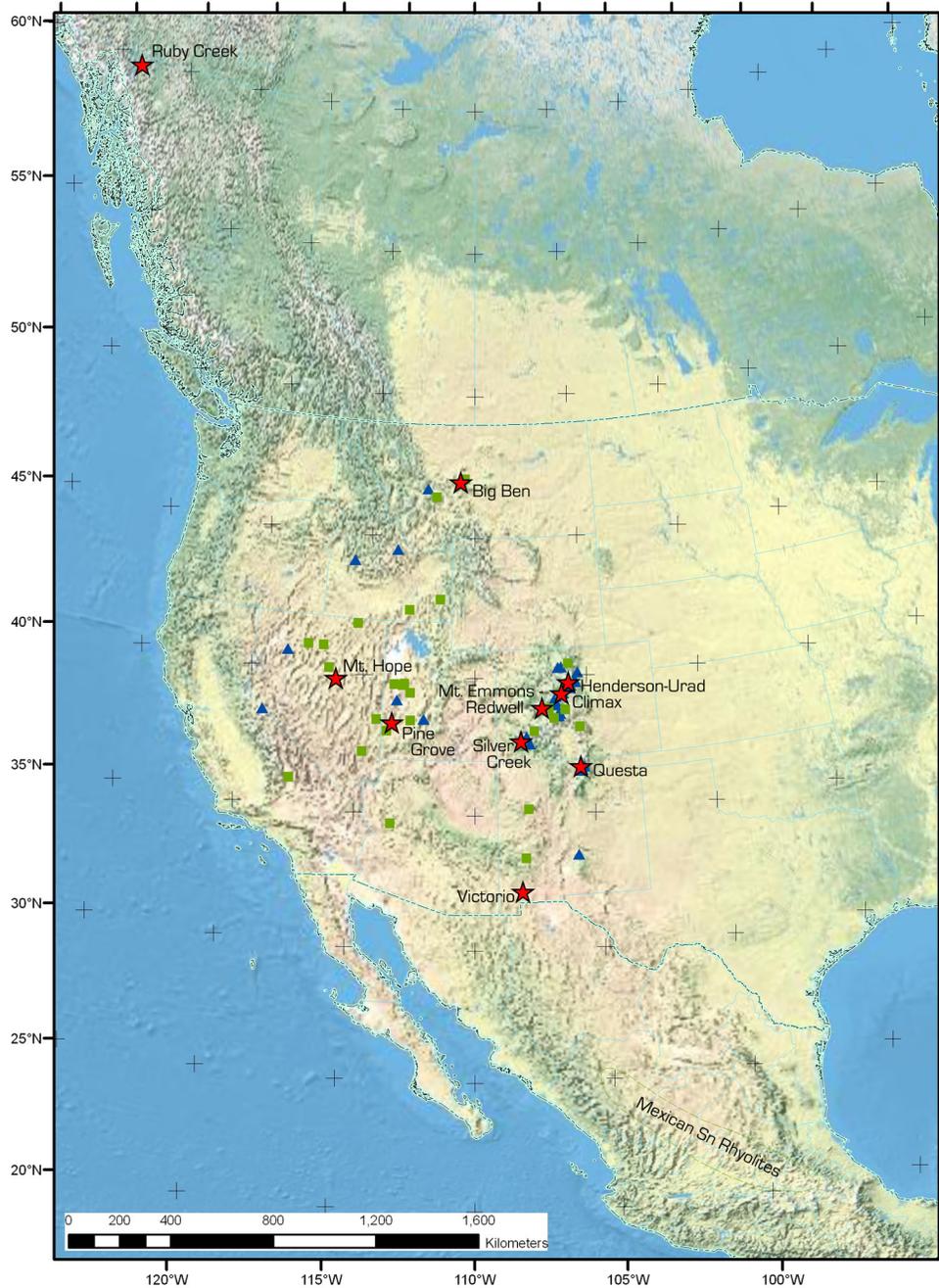


Figure 1. Location of Climax-type porphyry molybdenum deposits, prospects, and igneous centers with Climax-like compositions. Only the deposits (red stars) are labeled. Prospects are shown as blue triangles; igneous centers as green squares.

Climax-type deposits can be viewed as a special case of pluton-related deposits associated with rare-metal granites. Rare-metal granites are those associated with uncommonly high concentrations of normally dispersed elements such as F, Li, Rb, Cs, Sn, Ta, Nb, and Mo, and those granites may be calc-

alkaline I-type, peraluminous S-type, or peralkaline. Many tin, tungsten, and beryllium deposits are related to peraluminous granites, and zirconium and rare earth elements are commonly concentrated in peralkaline granites. Climax-type porphyry molybdenum deposits are invariably associated with calc-alkaline A-type granites.

Climax-type deposits are closely related to some alkaline-rock-related deposits within continental rifts in Norway and Greenland. They are also closely related to Sn- and W-rich porphyry deposits associated with collision-related S-type granites in Europe and Asia.

Most elements characterized as rare metals are concentrated in parts of Climax-type deposits, and both tin and tungsten have been recovered in small amounts during mining. Some of the deposits have associated silver-rich polymetallic veins, but these ancillary deposits have never been large sources of silver and base metals.

The classification of these deposits is problematic in several respects. The distinction between Climax-type deposits and low-fluorine porphyry molybdenum deposits is based primarily on the composition of associated plutonic rocks and particularly on the abundance of fluorine, rubidium, and other rare metals. Ruby Creek (formerly known as Adanac), in northern British Columbia, was classified by earlier authors as a low-fluorine deposit (Theodore, 1986; Sinclair, 1995), but recent studies have shown the associated rocks to have the characteristic F-Rb-Nb signature of Climax-type deposits (Ray and others, 2000).

A fundamental conundrum with respect to Climax-type deposits is their apparent restriction to North America. At the same time, North America hosts only a few of the W-Sn-Mo greisen and vein deposits (Laznicka, 2006) that are common in Asia. Nevertheless, the highly evolved source rocks for the two deposit types are, at least superficially, closely similar.

Molybdenum is the primary commodity in all known Climax-type deposits. It is almost exclusively found as molybdenite (MoS_2). Most of the elements characterized as rare metals are concentrated in parts of Climax-type deposits, and small amounts of wolframite, cassiterite, and monazite have been recovered from the Climax deposit. Henderson and Questa produce only molybdenum. No other Climax-type deposit has been mined. Other potential commodities include uranium, beryllium, rare earths, niobium, and tantalum.

Table 1 lists all the known Climax-type deposits.

Table 1. Climax-type Porphyry Molybdenum Deposits.

Deposit	Age (Ma)	Longitude	Latitude	Contained Mo (t)*	Primary reference
Climax, Colorado	33–24	-106.171	39.369	1,790,000	Wallace and others, 1968
Henderson, Colorado	30–27	-105.841	39.758	1,070,000	Shannon and others, 2004
Urad, Colorado	29	-105.835	39.760	29,100	Not available
Mt. Emmons, Colorado	17	-107.051	38.884	344,000	Thomas and Galey, 1982
Redwell Basin, Colorado	17	-107.057	38.890	18,400	Sharp, 1978
Silver Creek, Colorado	5	-108.008	37.698	124,000	Cameron and others, 1986
Questa, New Mexico	25	-105.508	36.717	442,000	Ishihara, 1967
Log Cabin, New Mexico	25	-105.570	36.688	53,400	Not available
Victorio, New Mexico	35	-108.103	32.180	112,000	McLemore and others, 2000
Pine Grove, Utah	23	-113.607	38.336	192,000	Keith and others, 1986
Mt. Hope, Nevada	38–26	-116.186	39.795	460,000	Westra and Riedell, 1995
Big Ben, Montana	51	-110.710	46.975	104,000	Johnson, 1964
Ruby Creek, British Columbia	84	-133.403	59.709	208,000	Pinsent and Christopher, 1995

*Molybdenum tonnage from Gregory Spanski, 2009, written commun.

Regional Environment

Climax-type deposits are found in a single region, the continental interior of western North America. All the deposits except Ruby Creek, British Columbia, were formed during extension subsequent to cessation of subduction of the Kula and Farallon plates beneath western North America. The alkalic deposits in Greenland and Norway, which are excluded from this model, are found within actual continental rifts, whereas the North American deposits are found in a broad extensional province that extends from the Rio Grande rift westward to the Sierra Nevada range.

The deposits in the United States range in age from 51 Ma at Big Ben, Montana, to 5 Ma at Silver Creek, Colorado. Ruby Creek, Canada is problematic, not just because of its Late Cretaceous age, but because it apparently occurs in a continental arc and several contemporaneous porphyry copper deposits are present along the length of the arc, both to the northwest and to the southeast.

Because the permeability of the rock that facilitates deposition of molybdenum is a result of hydrofracturing related to igneous emplacement, preexisting high-level structures are relatively unimportant in the localization of ore in Climax-type deposits. The deposits do not appear to form in clusters.

The deposits form when fluids exsolved from small intrusions in the upper crust precipitate molybdenite and quartz in veinlets. They are universally related to highly evolved silica- and fluorine-rich intrusions (rare-metal granites). The nature of host rocks for Climax-type deposits does not seem to affect the formation or location of the deposits.

Physical Description of Deposits

These deposits are remarkably similar to each other in structural setting and shape, differing primarily in size. Much of the size variation may be due to the successive overlap of multiple mineralizing events in the larger systems. The Henderson deposit, for example, is the cumulative effect of twelve events that combined to form three ore shells. Figure 2 shows a generalized picture of the successive intrusive and mineralizing events at Henderson, along with the resulting ore distribution.

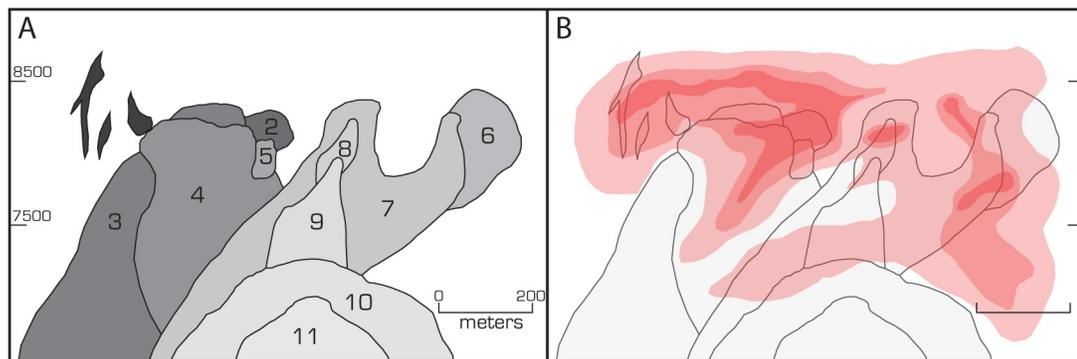


Figure 2. Relationship of multiple intrusions to ore at Henderson. Stocks are shown A, Numbered in order of age. Ore tenor is shown B, in successively deeper shades of red, >0.1 percent, >0.3 percent, and >0.5 percent MoS₂. After figure 14 in Carten and others (1988). The earliest stock (the Phantom) does not appear in this cross-section.

The deposits typically take the form of an inverted cup or hemisphere. At the largest deposit, Climax, these cups may have been as much as 1,000 meters (m) in diameter (White and others, 1981), whereas at Henderson they are approximately 400–700 m in diameter (see figures in Wallace and others, 1978). At Mt. Emmons, the ore body is about 600–700 m in diameter. The ore bodies in these large deposits are 100–200 m thick. Smaller deposits have smaller dimensions.

Because the plutons that both host and serve as the source of the ore bodies appear to originate at the base of the continental crust, upper crustal structures are unlikely to be important in controlling their distribution at continental scale. At the district scale, the rhyolite and granite intrusions associated with Climax-type deposits may be emplaced along preexisting linear structures in the basement. At the deposit scale, the permeability of the rock that facilitates molybdenum deposition is a result of hydrofracturing related to igneous emplacement and the symmetric radial and concentric dike systems commonly present indicate an isotropic environment.

Geophysical Characteristics

Because only one deposit, Pine Grove, Utah, is known only in the subsurface, information about the geophysical signatures of covered deposits is limited. The gravity signature will commonly be a negative anomaly, unless the deposit is emplaced in associated lower-density volcanic rocks. Similarly,

the magnetic signature will depend strongly on the differing magnetic properties of enclosing wall rocks. Induced polarization methods can detect high sulfide zones.

Ore Characteristics

The ore assemblage in Climax-type deposits differs little, and it is generally simple—molybdenite in quartz veins. Very small amounts of wolframite, cassiterite, sphalerite, or galena may be present in some of the veins, but the vast majority of the molybdenite in the deposits is contained in veins of quartz + fluorite ± molybdenite and K-feldspar + fluorite ± quartz ± molybdenite ± biotite (Seedorf and Einaudi, 2004a). At most deposits, the ore assemblage is reported to be quartz + molybdenite ± K-feldspar ± fluorite, but it may also contain biotite ± magnetite ± topaz ± rutile ± Na-feldspar ± garnet ± wolframite ± ilmenorutile ± muscovite.

Little zoning is recognized within the molybdenite-bearing ore bodies, which are generally composite and consist of numerous overlapping ore zones, each related to an individual stock (Carten and others, 1988; Seedorf and Einaudi, 2004a). Tungsten and tin minerals may be distal to molybdenite zones.

The molybdenite ore is almost entirely contained in brittle fractures related to the emplacement of the stocks and the release of hydrothermal fluids. Although there are some larger veins, and sometimes ore in breccias, most of the ore is in stockworks of crosscutting fractures of different generations. Disseminations and replacements are not characteristic.

Geochemical Characteristics

The trace-element signature of Climax-type deposits is distinctive and is an essential part of the definition of the deposit type. The source plutons for these systems nearly always contain Rb >250 ppm and Nb >20 ppm. Rubidium contents are commonly in excess of 500 ppm and niobium is commonly in excess of 50 ppm. Tantalum may be >2 ppm (or about a tenth of the Nb content). Strontium content is correspondingly low, always <100 ppm and commonly <5 ppm. In addition, most rocks from Climax-type systems have strikingly low zirconium contents, almost always <120 ppm and some <50 ppm. They may also be enriched in Be, Cs, Li, Sn, Th, and W (Mutschler and others, 1981; Westra and Keith, 1981).

Fluorine is almost always lost from igneous rocks during crystallization and cooling. Thus, measured fluorine concentrations in the rocks are commonly lower than in the magmas before crystallization. Nevertheless, any measured fluorine content above about 2,000 ppm can be taken as indicative of Climax-type deposits, and some rocks may contain >1 percent fluorine.

Elevated fluorine and uranium may be detected kilometers, even tens of kilometers, away from large deposits, although this feature is not well documented.

On the basis of fluid inclusion measurements, the molybdenite-bearing ore veins formed at very high temperatures, from about 400° Celsius (C) to >600° C, consistent with the temperatures at which the hydrothermal fluids were exsolved from the magmas (Bloom, 1981; Cline and Vanko, 1995; Klemm and others, 2004; Seedorff and Einaudi, 2004a; Rowe, 2005). Lower-temperature alteration assemblages described by Seedorf and Einaudi (2004a) formed at lower temperatures (200°–600° C). The highest-temperature inclusions are typically hypersaline and contain both halite and sylvite daughter minerals, whereas lower-temperature inclusions become progressively less saline.

Hydrothermal Alteration

At most deposits, the alteration zones have been termed potassic, sericitic, and propylitic, and the potassic zone is generally tightly confined to the volume occupied by quartz-molybdenite veins, whereas the sericitic zone is found primarily above (not lateral to) the ore body. The white micas in the sericitic zone are likely to be fluorine rich, and their fluorine content ranges from about 1 to 3 percent. Gunow and others (1980) found that white micas in the Henderson deposit contained about 10–50 mole percent of the fluorine end-member molecule, depending in part on the phengite content of the sericite.

In a detailed study at the Henderson deposit, Seedorff and Einaudi (2004a, b) defined three complex sets of alteration assemblages: high temperature, moderate temperature, and low-temperature. These assemblages are not found in broad zones that consist primarily of one assemblage, but rather they are zoned around individual veins and veinlets such that the highest-temperature assemblage is in the center. When these veins (which may be from distinct mineralization events—there are 12 events at Henderson) intersect, the resulting mineral patterns can be difficult to interpret.

The high-temperature alteration minerals formed, as did the ore, immediately above the stocks responsible for the deposits, and they coincide with or are located slightly above the ore bodies. The resulting high-temperature (alkali feldspar) alteration zones are relatively compact and similar in size to the ore bodies; individual zones generally occupy ≥ 1 square kilometer (km^2). The overlying sericitic zones above are composite and larger. The propylitic alteration zone that surrounds most deposits may be quite large, although it is sometimes difficult to distinguish from regional metamorphic assemblages. At Henderson, this zone is as large as 12×7.5 kilometer (km) (Seedorff and Einaudi, 2004a; Shannon and others, 2004). At Questa, much of the entire surrounding region is propylitically altered, but a zone about 4 km wide and as much as 15 km long has been specifically affected by hydrothermal alteration related to the molybdenite mineralization (Ludington and others, 2004).

In the high-temperature assemblages proximal to the ore bodies, the original rock-forming minerals are nearly completely replaced by alteration minerals, primarily quartz and K-feldspar. The distribution and abundance of alteration minerals is dependent on the sum of the vein types that contribute to the particular area under consideration.

The study of Seedorff and Einaudi (2004a) demonstrates that almost all the alteration minerals at Henderson formed in relatively narrow envelopes surrounding the veins. However, in some areas, multiple cycles of mineralization have successively introduced veins to the point that the rock appears to be pervasively altered. Within the envelopes of the high- and moderate-temperature assemblages, the original microscopic texture of the rocks is completely obscured, although quartz phenocrysts may still be recognized.

Weathering

Surface weathering of mineralized rock at Climax-type deposits is common, but it does not result in any observable enrichment, or development of abundant secondary molybdenum-bearing minerals.

Petrology of Associated Igneous Rocks

Climax-type porphyry molybdenite deposits are closely related to a specific suite of high-silica granites and rhyolites. Specifically, the rocks are strongly enriched in rubidium, niobium, and fluorine and are strongly depleted in strontium and zirconium. Rocks of this composition are apparently not formed during subduction. They are formed by interaction of mantle-derived melts with high-grade metamorphic rocks at the base of the continental crust, and they form exclusively in extensional tectonic

environments. The granites and rhyolites are typically magnetite-bearing and are commonly characterized as A-type magmas.

Theory of Deposit Formation

The way in which individual ore shells are derived from individual small plutons is reasonably well understood. A fluorine- and chlorine-rich hydrothermal fluid separated from the crystallizing apex of a pluton and moved primarily upward. This fluid, which contained the molybdenum that forms the ore deposit as well as other metals (tungsten, silver, base metals) that were deposited distal to the ore, evolved compositionally as it cooled and moved upward. The molybdenum was deposited in quartz veins within a few hundred meters of the apex of the stock, whereas the other metals were generally deposited at greater distances.

Another factor that may play a part in the formation of Climax-type deposits is the profound change in solubility of water and other volatiles in magmas that is a result of elevated fluorine content. The amount of fluorine fixed in the ore and the alteration envelopes that surround Climax-type systems is very large. Cubic kilometers of rock may contain in excess of 0.5 percent fluorine. The high magmatic fluorine content may result in the formation of an immiscible melt, one that may contain >10 percent fluorine and is extremely rich in aluminum, potassium, and sodium. Experimental and field studies that demonstrate this phenomenon are summarized in Gramenitskiy and Shekina (1994). If such low-density fluids concentrate molybdenum also, they could play an important part in scavenging molybdenum and transporting it to the top of the magma column. Evidence for such a fluid is unlikely to be prominently preserved, because most of the minerals that would eventually precipitate are alkali fluorides, which are extremely soluble in water even at moderate temperatures. In addition, the well-known depression of the solidus in F-rich (and B- and Li-rich) granitic melts (Manning, 1981; Manning and Pichavant, 1985) can help to explain the crystal-poor nature of the rhyolite porphyry stocks found in Climax-type systems.

Stein and Hannah (1985) and Stein (1988) have shown conclusively, using lead, sulfur, and oxygen isotope ratios, that the metals and sulfur were derived entirely from within the stocks, and that the melts formed from high-grade metamorphic rocks at the base of the crust. The fact that these stocks are invariably enriched not only in Mo, but also in a common suite of elements (F, Rb, Nb, Ta, and other rare metals) suggests that extreme magmatic differentiation is probably at least partially responsible for the unique composition of the magmas responsible for Climax-type deposits. The fact that the deposits (and similar unmineralized high-level rhyolites) are consistently found in a post-subduction, extensional environment suggests that the melting conditions and composition of the source region must also have an influence. Why these factors combined to form numerous Climax-type deposits primarily in western North America, whereas similar A-type granites on other continents do not have such deposits associated with them, remains unanswered.

Geoenvironmental Features

By Geoffrey S. Plumlee

The original geoenvironmental description of Climax-type deposits of Ludington and others (1995) can be updated to include substantial new data from the mined Questa deposit and adjacent

unmined deposits along the Red River, New Mexico (see overview by Nordstrom, 2008, and many references therein: Ludington and others (2004), and Agency for Toxic Substances and Disease Registries (2005)). Limited data are also available for Climax (Plumlee and others, 1999), Urad (Trlica and Brown, 2000), and the Climax-like Malmbjerg, Greenland, deposit (Barnes and others, 2009).

Environmental Conditions Before Mining

Premining environmental conditions of Climax-type deposits can differ substantially depending upon the depth to which each deposit was exposed by erosion. Where erosion has exposed stockwork quartz-sericite-pyrite (QSP) alteration, sulfide oxidation can lead to the formation of natural acid-rock drainage in the near-surface environment. This drainage is characterized by low pH (from 2.5 to 3–4) and high to relatively high concentrations (compared with natural waters draining other mineral-deposit types) of dissolved calcium and sulfate (hundreds to several thousand milligrams per liter), iron and aluminum (several hundreds of milligrams per liter), manganese and zinc (several tens of milligrams per liter), and fluorine (as much as ~20 milligrams per liter (mg/L)). Molybdenum concentration in natural drainage waters are typically several hundred micrograms per liter or less. At Questa, there are sufficient quantities of carbonate minerals in the QSP alteration and main ore zones so that deeper groundwaters (out of contact with atmospheric oxygen) have nearly neutral pH but elevated concentrations of sulfate and some metals such as manganese. In deposits where carbonate minerals are not abundant, acid ground waters can persist to depths well below the surficial environment.

At Questa, near-surface intense acid sulfate weathering of stockwork QSP ore zones led to the formation of large, denuded, erosional scars with steep slopes and high rates of chemical weathering and physical erosion. The weathered material, which forms a relatively thin veneer (2 to ~30 m thick) on top of unweathered bedrock, is composed of fragments of unweathered mineralized rock in a matrix of clays, jarosite, goethite, gypsum, and other soluble sulfate salts. The weathering process can transform structurally competent, unweathered QSP-altered rock into slump-prone weathered material in time frames perhaps as short as decades to centuries. Large alluvial fans typically develop immediately downstream of the scars and are composed of weathered and unweathered mineralized rock fragments eroded from the scars.

Climax-type deposits with mineralization focused around a single intrusive center may have outcrops of QSP-altered rocks covering 3–5 km². Where multiple intrusive and mineralizing centers are present, such as along the Red River near Questa, the total surface area occupied by QSP-altered rocks in a particular mineralized area may exceed 20 to 30 km².

The effect on surface-water quality due to natural inputs of water or sediment from a Climax-type mineralized area can extend many kilometers downstream from the mineralized area. At Questa, mineralized sediment eroded from the scars and their associated alluvial fans can have a short-term detrimental effect on water quality and aquatic habitat as a result of storm runoff.

Potential Environmental Considerations Related to Mining or Mineral Processing

Climax-type deposits are mined by large-scale underground block caving or aboveground open-pit methods. Surface areas of open pits and associated waste dumps are typically 5–10 km², whereas the area occupied by block caving operations is less than 5 km².

Mine-waste characteristics will depend on the types of mineralization and alteration that need to be removed to access the central ore zone. Waste piles composed of QSP-altered rocks will likely produce acidic drainage waters with highly elevated sulfate (several thousands of milligrams per liter) and calcium, aluminum, and iron (hundreds to over 1,000 mg/L). Depending upon the deposit, other elements are present in lower concentrations, including manganese and fluorine (tens to hundreds of

milligrams per liter); zinc and nickel (tens to hundreds of milligrams per liter); and copper, uranium, and rare-earth elements (several milligrams per liter). Limited data for molybdenum concentrations in mine-drainage waters from Climax-type systems generally indicate levels below 1 mg/L.

Waste piles developed from rocks below the primary QSP zones in deposits with abundant carbonates (such as Questa) develop less acidic waters with correspondingly lower concentrations of most metals, with the exception of manganese, zinc, and molybdenum.

The relatively rapid chemical weathering and physical erosion of QSP-altered, stockwork-mineralized rocks in the erosional scars at Questa and along the Red River indicate that similar rocks placed into waste piles may tend to break down relatively rapidly, potentially leading waste-pile instability with time.

Processing of mined Mo ores is typically accomplished by grinding and froth flotation to produce a molybdenite concentrate. Tailings impoundments for Climax-type operations can cover 5 to 10 km² of area in addition to the area occupied by the mine site and mine waste piles. If present in the primary ores, acid-neutralizing carbonates will likely end up in the tailings solids, as will acid-generating iron sulfides. Ores with high levels of carbonate minerals will likely generate less acidic to near neutral tailings waters. In carbonate-poor tailings with abundant iron sulfides, sulfide oxidation in the near surface will likely produce acidic waters, whereas waters within the tailings that are out of contact with the atmosphere may have near-neutral pH. Metals and metalloids in the tailings waters will likely be similar to those found in mineralogically similar mine wastes.

Potential Health Considerations

The elevated levels of fluorine found in natural and mining-related waters from Climax-type deposits raise the potential for the development of fluorosis in any wildlife that regularly consume these waters. Human consumption of these waters, though unlikely, should accordingly be minimized. The weathering of fluorine and molybdenum from these deposits into soils and waters, and its subsequent uptake by vegetation, may also present the potential for development of molybdenosis or fluorosis in ruminant wildlife that consume the vegetation.

The typically elevated concentrations of uranium found in the intrusive rocks associated with mineralization suggest that radon exposures may be an issue in underground mines or mine facilities built on the intrusive rocks.

Concentrations of potentially toxic elements such as cadmium, lead, arsenic, and antimony, although relatively low in natural or mining-related drainage waters, have been noted by the Agency for Toxic Substances and Disease Registries (2005) to be high enough in groundwater near the Questa mine to be of potential health concern if the water is used for human consumption. However, the Agency for Toxic Substances and Disease Registries (2005) report found no indications of such current usage.

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