



# Low-fluorine Stockwork Molybdenite Deposits

By Steve Ludington, Jane Hammarstrom, and Nadine Piatak

Open-File Report 2009–1211

U.S. Department of the Interior  
U.S. Geological Survey

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Suggested citation:  
Ludington, Steve, Hammarstrom, Jane, and Piatak, Nadine, 2009, Low-fluorine stockwork molybdenite deposits: U.S.  
Geological Survey Open-File Report 2009–1211, 9 p.

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# Low-fluorine Stockwork Molybdenite Deposits

## Abstract

Low-fluorine stockwork molybdenite deposits are closely related to porphyry copper deposits, being similar in their tectonic setting (continental volcanic arc) and the petrology (calc-alkaline) of associated igneous rock types. They are mainly restricted to the Cordillera of western Canada and the northwest United States, and their distribution elsewhere in the world may be limited. The deposits consist of stockwork bodies of molybdenite-bearing quartz veinlets that are present in and around the upper parts of intermediate to felsic intrusions. The deposits are relatively low grade (0.05 to 0.2 percent Mo), but relatively large, commonly >50 million tons. The source plutons for these deposits range from granodiorite to granite in composition; the deposits primarily form in continental margin subduction-related magmatic arcs, often concurrent with formation of nearby porphyry copper deposits. Oxidation of pyrite in unmined deposits or in tailings and waste rock during weathering can lead to development of acid-rock drainage and limonite-rich gossans. Waters associated with low-fluorine stockwork molybdenite deposits tend to be nearly neutral in pH; variable in concentrations of molybdenum (<2 to >10,000 µg/L); below regulatory guidelines for copper, iron, lead, zinc, and mercury; and locally may exceed guidelines for arsenic, cadmium, and selenium.

## Geologic Features

By Steve Ludington

Low-fluorine stockwork molybdenite (MoS<sub>2</sub>) deposits are closely related to porphyry copper (Cu) deposits, being similar in their tectonic setting (continental volcanic arc) and the petrology (calc-alkaline) of associated igneous rock types. They are mainly restricted to the Cordillera of western Canada and the northwest United States, and their distribution elsewhere in the world may be limited. Figure 1 shows the location of some of the major known deposits.



**Figure 1.** Location of well-known low-fluorine stockwork molybdenite deposits, shown as violet stars.

The deposits consist of stockwork bodies of molybdenite-bearing quartz veinlets that are present in and around the upper parts of intermediate to felsic intrusions. The deposits are relatively low-grade (0.05 to 0.2 percent Mo), but relatively large, commonly >50 million tons. They primarily form in continental margin subduction-related magmatic arcs, often concurrent with formation of nearby porphyry copper deposits.

Literature that provides the basis for this model includes the two abbreviated models of Theodore (1986) and Sinclair (1995), as well as papers in two important compilation volumes published

by the Canadian Institute of Mining and Metallurgy (Sutherland Brown, 1976; Schroeter, 1995) and the summary in Sinclair (2007). Company Web sites were also an important information source.

### **Associated Deposit Types**

This model is restricted to deposits that contain negligible copper and are not related to evolved, high-fluorine granites. Deposits included in the present model generally contain <100 ppm Cu in ore.

Several deposits (Red Bird, British Columbia; Mount Tolman, Wash.; Cumo, Idaho; Hall, Buckingham, and B&C Springs, Nev.) that were considered to be low-fluorine molybdenite deposits in earlier compilations are now considered to be porphyry copper deposits, albeit Mo-rich. Their copper grades are no lower, and molybdenum grades no higher, than several of the most Mo-rich porphyry copper deposits in the Singer and others (2008) database of world porphyry copper deposits. Some of the Canadian deposits contain appreciable tungsten (W) and may be better considered to be W-Mo greisen and (or) vein deposits (Gem, British Columbia).

Low-fluorine stockwork molybdenite deposits do not form in the same regions or tectonic environments as Climax-type porphyry molybdenite deposits. Rather, they form in the same regions and at the same times as subduction-related porphyry copper deposits.

### **Commodities**

Molybdenum is the only commodity recovered from known low-fluorine stockwork molybdenite deposits, although some deposits contain small amounts of tungsten, as scheelite or wolframite. There is relatively little information compiled and available about trace constituents of low-fluorine deposits.

### **Example Deposits**

The overwhelming majority of the world's known low-fluorine stockwork molybdenite deposits are found in North America. Whether this is an accident, due to the fact that this is the primary place in which they have been sought or some other reason, is uncertain. Table 1 lists the best known deposits in North America. Endako, Boss Mountain, Kitsault, and Thompson Creek have been exploited.

There are about 100 deposits worldwide that have been reported to be bulk-mineable, porphyry-style deposits of molybdenum. Most of these are in Russia, China, Kazakhstan, and Mongolia. Present information is insufficient to either include or exclude them from this model.

**Table 1.** Low-fluorine porphyry molybdenite deposits in North America.

Deposit	Age (Ma)	Longitude	Latitude	contained Mo (t)	Primary reference
Red Mountain, Yukon	87	-133.750	60.983	181,000	Brown and Kahlert, 1986
Mt.Haskin, B.C.	53	-129.505	59.346	11,000	Velocity Minerals Ltd. Web site
Storie, B.C.	73	-129.867	59.217	68,100	Columbia Yukon Explorations Inc. Web site
Ajax, B.C.	54	-129.400	55.583	225,000	Woodcock and Carter, 1976
Mt. Thomlinson, B.C.	54	-127.483	55.583	29,500	B.C. MINFILE
Tidewater, B.C.	53	-129.545	55.468	18,100	Woodcock and Carter, 1976
Bell Molybdenum, B.C.	52	-129.333	55.450	21,500	Woodcock and Carter, 1976
Kitsault, B.C.	54	-129.425	55.417	157,000	Woodcock and Carter, 1976
Roundy Creek, B.C.	54	-129.650	55.417	18,100	Woodcock and Carter, 1976
Quartz Hill, Alaska	27	-130.482	55.403	1,060,000	Wolfe, 1995
Hudson Bay Mountain, B.C.	71	-127.300	54.817	154,000	Woodcock and Carter, 1976
Serb Creek, B.C.	Mesozoic	-127.755	54.651	22,500	B.C. MINFILE
Endako, B.C.	144	-125.113	54.036	225,000	Bysouth and Wong, 1995
Lucky Ship, B.C.	51	-127.483	54.033	47,800	Nanika Resources Inc. Web site
Boss Mountain, B.C.	102	-120.933	52.100	219,000	Soregaroli, 1975
Max (Trout Lake), B.C.	76	-117.600	50.633	60,000	Boyle and Leitch, 1983
Salal Creek, B.C.	8	-123.406	50.769	n/a	B.C. MINFILE
Gem, B.C.	Miocene?	-121.714	49.717	36,900	Saturn Minerals Inc. Web site
Carmi, B.C.	50	-119.167	49.517	22,800	Hi Ho Silver Resources Inc. Web site
Cannivan Gulch, Montana	67	-112.956	45.655	195,000	Worthington, 2007
Thompson Creek, Idaho	86	-114.550	44.314	256,000	Hall and others, 1984
Little Boulder Creek, Idaho	85	-114.558	44.058	110,000	Worthington, 2007

The Contained Mo figures are very preliminary; many deposits are under active exploration, with resources increasing yearly. B.C. = British Columbia, Canada; B.C. Minfile = British Columbia Ministry of Energy, Mines, and Petroleum Resources (2009).

## Regional Environment

All well described low-fluorine stockwork molybdenite deposits are in the North American Cordillera, in western Canada and northwestern United States, in a post-accretionary setting. They were formed during subduction of the Kula and Farallon plates beneath western North America. They are as old as 144 Ma (Endako) and as young as 8 Ma (Salal), but most are Late Cretaceous (about 100–70 Ma) and early Tertiary (about 60–50 Ma). All of them were emplaced in continental magmatic arcs. Sinclair (2007) relates Quartz Hill and Mt. Haskin to local extension adjacent to strike-slip faults.

The deposits generally are found near the margins of the source plutons, which range in composition from granodiorite to granite. The ore is in fractures caused by hydrofracturing resulting from the exsolution of magmatic-hydrothermal fluids from cooling plutons, and linear high-level structures are relatively unimportant in controlling the location of ore. The deposits generally do not form in clusters, although the Alice Arm deposits (Ajax, Tidewater, Bell, Kitsault, and Roundy Creek) are an important exception.

## Physical Description

The ore zones commonly are elliptical, circular, crescentic, or annular in cross-section and cylindrical, tabular, or irregular in the vertical dimension. The dimensions of orebodies are commonly

hundreds of meters across and may be hundreds of meters in vertical extent. The nature of the rocks that host the plutons and deposits appears to be unimportant; deposits are present both in associated volcanic rocks and in much older country rocks. The deposits are all post-accretionary and are not conspicuously aligned along upper crustal structures.

## Geophysical Characteristics

There is limited literature describing the geophysical characteristics of low-fluorine stockwork molybdenite deposits. The gravity signature will commonly be a negative anomaly, unless the deposit is emplaced in lower-density associated volcanic rocks. Similarly, the magnetic signature will depend strongly on the magnetic properties of enclosing wall rocks. Induced polarization methods can detect high sulfide zones.

## Ore Characteristics

Molybdenite-bearing quartz veinlets commonly contain small amounts of pyrite, and may also contain trace amounts of magnetite, scheelite, wolframite, galena, or sphalerite; chalcopyrite is rare. The veins may also contain K-feldspar±biotite±sericite±clay minerals±calcite±anhydrite as gangue minerals.

The veins are generally not composite, and all the major ore and gangue minerals seem to have formed contemporaneously. Peripheral polymetallic (Ag-Pb-Zn; silver-lead-zinc) veins are present at some deposits, but zonation within a single set of veins is not documented at any of the deposits. In addition to stockwork veinlet systems, larger veins, sets of veins, and ore-bearing breccias are sometimes present.

## Geochemical Characteristics

There are no compiled data on the trace-element composition of igneous rocks associated with this group of deposits.

Endako is the only low-fluorine deposit where a detailed study of fluid-inclusion temperatures and compositions has been made (Selby and others, 2000). At Endako, ore fluids display homogenization temperatures of about 360 to 560°C. and are mostly of moderate salinity (<15 wt. percent NaCl equiv.). Similar low salinities are indicated for Hudson Bay Mountain (Bloom, 1981) and Max (Linnen and Williams-Jones, 1990). Oxygen and hydrogen isotope values of altered rocks do not reflect purely magmatic compositions, and they suggest the involvement of meteoric water in the ore-forming fluid (Selby and others, 2000).

## Hydrothermal Alteration

Alteration assemblages are similar to those found in porphyry copper deposits. A central zone of potassic (and sometimes silicic) alteration is characterized by quartz±K-feldspar±biotite±anhydrite. Distal to the potassic zone, phyllic alteration is present. The phyllic mineral assemblage is primarily quartz±sericite±carbonate minerals. Surrounding this may be a large propylitic zone (epidote+chlorite) which can extend for hundreds of meters, although this alteration is sometimes difficult to distinguish from regional metamorphic assemblages. Argillic alteration, consisting of clay minerals such as kaolinite and montmorillonite, whereas not common, may also be present, most typically as an irregularly distributed overprint on earlier alteration zones.

Areas of potassic alteration closely mimic the ore zones, whereas the phyllic alteration zone may be somewhat larger, extending hundreds of meters away from ore. Almost all the deposits crop out, so



little is known about the upper parts of the alteration systems. The propylitic zone may be much larger, perhaps kilometers in extent. Potassic alteration appears to occur in vein envelopes and becomes pervasive only where veins are closely spaced. Phyllic alteration, whereas still vein-controlled, may be more pervasive, as the alteration envelopes are generally wider.

## **Weathering**

Formation of enriched supergene mineralization due to weathering is not a factor in low-fluorine deposits, as molybdenum is not easily transported in the supergene environment. The weathering profile, which may include thick regolith and leached caps, has hampered exploration in northern British Columbia, Yukon, and Alaska.

## **Petrology of Associated Igneous Rocks**

The source plutons for these deposits range from granodiorite to granite in composition, although quartz monzonite may be the most common. Soregaroli and Sutherland Brown (1976) stated that, as a group, the rocks are more silicic than those related to porphyry copper deposits, but few data have been published to confirm this statement. The rocks are commonly porphyritic. Trace-element compositions apparently are consistent with normal, subduction-related calc-alkaline rocks. Some of the plutons are ilmenite-bearing (Sinclair, 2007).

## **Theory of Deposit Formation**

It can be postulated that the molybdenite orebodies in low-fluorine stockwork molybdenite deposits formed when hydrothermal fluids exsolved from crystallizing plutons and precipitated molybdenite as they cooled, entered lower-pressure environments, and were diluted with meteoric waters. The lack of detailed geochemical, isotopic, alteration, and fluid-inclusion studies precludes a more detailed discussion, as well as speculation on how the genesis of low-fluorine stockwork molybdenite deposits differs from that of porphyry copper deposits.

## **Geoenvironmental Features**

By Jane M. Hammarstrom and Nadine Piatak

Molybdenite ( $\text{MoS}_2$ ) is the primary ore mineral in low-fluorine stockwork molybdenite deposits. Unlike most other sulfide minerals, molybdenite releases molybdenum as an anion rather than as a cation during weathering. The geochemical mobility of molybdate anions increases with alkalinity in contrast to most metallic cations, such as copper. Molybdenite can oxidize to form Mo-bearing iron hydroxides or the mineral ferrimolybdate,  $\text{Fe}^{3+}_2(\text{MoO}_4)_3 \cdot 7(\text{H}_2\text{O})$ . Oxidation of pyrite in unmined deposits or in tailings and waste rock during weathering can lead to development of acid-rock drainage and limonite-rich gossans. Chalcopyrite, scheelite, and galena may be present as minor constituents. Pyrite and rare chalcopyrite can produce acid upon oxidation; calcite, a typical mineral in veins in these deposits, can neutralize the acid.

## Environmental Conditions Prior to Mining

Soils near low-fluorine porphyry molybdenite deposits typically contain molybdenum concentrations on the order of 15 to 2,000 ppm molybdenum, which is significantly higher than the median value of 1 ppm for United States soils (Kubota, 1977). Stream and lake sediments routinely are sampled during mineral exploration, where anomalies of tens to hundreds of ppm molybdenum have been measured near the deposits. Concentrations of elements of potential environmental concern, such as arsenic, cadmium, chromium, mercury, nickel, lead, and zinc in sediments and soils typically are below regulatory guidelines.

Streams draining these mineral deposits may have elevated concentrations of dissolved molybdenum. Typical molybdenum concentrations in freshwater systems in the United States are about 1 µg/L molybdenum. Waters with >10 to 20 µg/L molybdenum are likely a consequence of human activity such as mining, milling, smelting, coal-fired power plants, and agriculture or reflect natural background levels in areas with molybdenum deposits. Waters associated with low-fluorine stockwork molybdenite deposits tend to be nearly neutral in pH; variable in concentrations of molybdenum (<2 to >10,000 µg/L); below regulatory guidelines for copper, iron, lead, zinc, and mercury; and locally may exceed guidelines for arsenic, cadmium, and selenium. Contributions from other deposit types within drainage areas may explain much of the variability in the water chemistry data.

## Potential Environmental Considerations Related to Mining or Mineral Processing

Low-fluorine stockwork molybdenite deposits are mined by open-pit methods. Ore is crushed on site and ground using semiautogenous (SAG) grinding mills and ball mills. Mill output is passed to flotation cells where reagents are added, the molybdenite-laden froth is skimmed off the top, and the waste material is drawn from the bottom, reprocessed, and eventually released to tailings piles. In modern facilities where pyrite is a concern, because of acid rock generation from tailings, the tailings are floated to remove pyrite as a concentrate or are blended with alkaline material and pumped to subaqueous deposition in a tailings pond to prevent oxidation and acid generation. The tonnages of tailings are essentially the same as the tonnages of the deposits, because of the low percentages of ore minerals. Concentrations of metals in tailings are variable, depending on the mineralogy of a given deposit. Tailings from low-fluorine porphyry molybdenite deposits tend to be non-acid-generating unless the deposit is particularly rich in pyrite.

Waters associated with mine waste are near-neutral; molybdenum concentrations may exceed the World Health Organization drinking water guideline of 70 µg/L (World Health Organization, 2003) and may need to be treated before discharge to the environment. Molybdenum concentrations of tens to hundreds of mg/L are stated to pose little to no risk to aquatic organisms (Mine Environment Neutral Drainage Program, 2008). The Canadian freshwater criterion for the protection of aquatic life is 73 µg/L molybdenum, based on chronic toxicity for rainbow trout with an order of magnitude scale factor (Mine Environment Neutral Drainage Program, 2008).

Molybdenum is an essential trace element for plants; most plants can tolerate high concentrations of molybdenum. Plants growing in near-neutral to alkaline (pH>6.5) soils typically are enriched in molybdenum relative to plants growing in acidic (pH<5.5) soils. Although not toxic to plants, high molybdenum concentrations can cause molybdenosis, a type of molybdenum toxicity that results in a copper deficiency in ruminant animals (particularly in cattle and sheep) when they consume molybdenum-rich forage. Molybdenum reacts with sulfur in the rumen to form thiomolybdate complexes that render copper biologically unavailable. Wildlife (particularly moose) and domestic

animals feeding on plants growing on lands with elevated molybdenum may be at risk for molybdenosis, especially where waste rock has been treated with alkaline material such as lime, which can exacerbate molybdenum mobility (Mine Environment Neutral Drainage Program, 2008).

Chemical effects of submarine tailings disposal, a practice used for some coastal mines, have not been documented. Potential effects however, include changes in bottom habitat, changes to productivity from suspended sediments in the upper water column, and smothering effects to marine life.

## Potential Health Considerations

Insoluble molybdenum compounds such as MoS<sub>2</sub> (molybdenite) are non-toxic (Barceloux, 1999). Industrial occupational exposure to dust and fumes of soluble molybdenum trioxide and molybdates constitute greater hazards to human health than exposure to MoS<sub>2</sub> (International Molybdenum Association, 2009). Cattle and sheep are more susceptible than humans to molybdenum poisoning due to chronic exposure.

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