

The Boss Mountain molybdenum deposit, central British Columbia

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ABSTRACT

Molybdenum mineralization at Boss Mountain is hosted by the Triassic Takomkane quartz monzodiorite batholith and is associated with a Cretaceous monzogranite stock. Ore has been mined from a sheeted vein system that describes a partial annulus centred upon the apical region of the stock and from subvertical breccia pipes that emanate from the stock. Molybdenite precipitation is coincident with CO₂ effervescence from a dilute (1.9 mole % NaCl equivalent) hydrothermal fluid over a temperature range of 250°C to 370°C at a pressure of approximately 350 bars, interpreted to be greater than or equal to the lithostatic load and equivalent to a depth of 1.3 km or less.

Introduction

The chemical and thermal constraints on molybdenum transport and deposition to form molybdenum ore deposits are not well understood. To address this problem, the Boss Mountain mine in central British Columbia, operated by Noranda Mines Ltd., was chosen as a well-described (Soregaroli and Nelson, 1976), relatively small and simple example of a Cordilleran MoS₂ deposit. It is situated on the northeast slope of Takomkane Mountain, 10 km west of the community of Hendrix Lake (N.T.S. 93A/2W; latitude 52°06'N, longitude 120°56'W). Access is from 100 Mile House by nearly 90 km of road, the first 50 km of which are paved.

History

Gold prospectors reported a molybdenite occurrence in the area in 1911. In 1917, approximately 450 kg of molybdenite ore were transported by mule trail to Lac La Hache, 50 km to the west of the occurrence. Between 1928 and 1935, 103 mineral claims were located in the area of the showing, and in 1930 the property was acquired by the Consolidated Mining and Smelting Company Limited, which conducted surface exploration by trenching. In 1942, the British Columbia Department of Mines drilled approximately 400 m of X-ray core. In 1956, Climax Molybdenum Company Limited optioned the property from H.H. Huestis and Associates. Climax and their associates conducted 11 277 m of diamond drilling and limited bulldozer trenching; the option was dropped in 1960. Noranda Exploration Company Limited optioned the property in March 1961 and conducted further exploration which indicated that underground exploration was warranted. A 1.7 km adit (2.74 m by 2.74 m) was completed by March 1963; subsequent diamond drilling indicated an ore reserve in excess of 2 million tonnes and led to a production decision.

Between 1965 and 1971 a total of 2 968 740 tonnes of ore were milled, at an average grade of 0.260% Mo. Between 1974 and 1980 a further 3 603 440 tonnes of ore were milled at an average grade of 0.188% Mo. During the period 1977 to February 1983, the average operating cost was \$15.68 per tonne.

Underground mining commenced with breccia bodies and progressed to a larger tonnage, but lower grade, sheeted vein complex, mined by both underground and open pit methods. Underground mining employed longhole open stoping with sublevels at 30 m intervals. Drill patterns were based upon 2 inch (5 cm) drill holes, approximately 1.5 m apart, with an average hole length of 15 m, yielding 3 tonnes to 7 tonnes per metre drilled; powder factor averaged 0.23 kg per tonne and secondary blasting powder consumption ranged from 0.1 kg to 0.6 kg per tonne. In the underground operation, broken muck was removed from drawpoints with 0.76 m³ Scooptrams and dumped into chutes on the production level; whereas open pit mining utilized a conventional loader and truck operation. In the open pits, face height was 7.6 m with a berm left on every second bench. The drilling pattern involved 16.5 cm blastholes on a rectangular 3.7 m by 4.9 m grid. No electric power was used beyond the pit shop. Ore was delivered 2.4 km to the mill crusher by 35 ton trucks travelling downhill on an 8% grade. The open pit circuit had a capacity of 1090 tonnes per day, while the underground circuit averaged 1360 tonnes per day for optimal recovery. Waste to ore ratio was 1:1 over the mine life.

The concentrator was manually controlled and utilized fully autogenous grinding for the open pit ore and a conventional ball mill for underground ore; cyanide was eliminated from the flotation process by employing Orafam D8 as a key reagent.

Mining terminated indefinitely in November 1982, due to adverse market conditions. At this time, Noranda Mines Limited estimated an in situ reserve of approximately 7.4 million tonnes of material containing in excess of 0.1% Mo. After mothballing the plant and townsite, a comprehensive reclamation program was initiated. Waste rock dumps were reshaped and contoured before being fertilized and seeded several times. Steep open stopes were perimeter-drilled and blasted to create stable slopes, eliminating undercuts and crown pillars. The tailings are non-acid generating and were seeded and fertilized with clover, alfalfa and red fescue. Monitoring of run-off water from the site over a ten-year period since shut down has produced results well within permitted levels. The site was placed on care and maintenance until 1991.

Regional Geology

The Boss Mountain deposit is situated in the eastern flank of the Intermontane, or Interior Structural Belt (Sutherland Brown,

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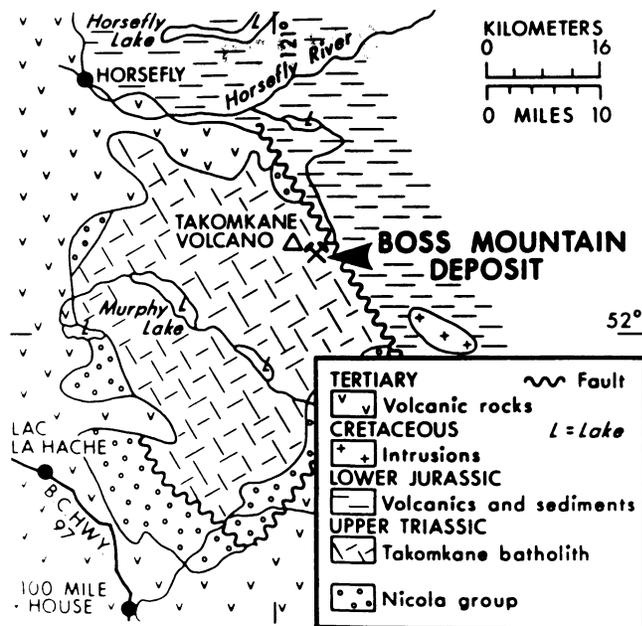


FIGURE 1. Geology of the Boss Mountain area (from Soregaroli and Nelson, 1976).

1969). In the mine area, the Intermontane Belt comprises an elevated 1500 m plateau characterized by Mesozoic volcanic and sedimentary strata (Sutherland Brown, 1969). Boss Mountain occurs within the Quesnel Trough (Campbell and Tipper, 1970) defined by the occurrence of Upper Triassic and Lower Jurassic volcanic and sedimentary rocks which contain later intermediate and acidic intrusions.

The molybdenum deposit is contained in the Takomkane batholith (Fig. 1) that intrudes Upper Triassic Nicola Group volcanic rocks, suggested by Campbell and Tipper (1970) to be the Takomkane's extrusive equivalent. The batholith is in fault contact with Lower Jurassic volcanic and sedimentary rocks to the east (Fig. 1).

Middle Cretaceous monzogranite to granodiorite bodies intrude all older units. A belt containing these intrusions extends for 130 km to the southeast. The most northerly body known within the belt, the Boss Mountain stock (Fig. 2), intruded the Takomkane batholith within a kilometre of its fault bounded eastern flank (Fig. 1) and is associated with molybdenum mineralization at Boss Mountain (Soregaroli, 1968).

The post-mineralization Tertiary geology of the area is described

by Campbell (1963), Wilson (1977) and Fujii and Scarfe (1981), and Pleistocene geology by Tipper (1971).

Local Geology

Ore at Boss Mountain occurs within the Takomkane batholith (Fig. 2), a composite intrusion comprising of at least four rock types (Macdonald, 1983); monzogranite and quartz monzogranite ("di-orite" and "granodiorite" members of the Takomkane batholith; Soregaroli, 1968); minor phases of the batholith include biotite porphyry and hornblende porphyry. All other rock types in the immediate mine area are younger than the Takomkane batholith. Quartz-orthoclase-plagioclase-tourmaline (\pm magnetite, sphene) pegmatites cut the batholith. Their age relationship with respect to mineralization was not established by the authors, although Soregaroli (1968) considers them to be older.

Intrusion of a mafic and felsic igneous complex accompanied mineralization. Basaltic to basaltic-andesitic dikes were considered by Soregaroli (1968) to be premineralization. Subsequent mining developments on surface and underground revealed exposures that indicated emplacement of both mafic and felsic intrusions took place during the mineralizing event. Mafic intrusions during mineralization include both tholeiitic and alkali basaltic dikes (Macdonald, 1983). The Boss Mountain stock, an adamellite or monzogranite (classification of Streckeisen, 1973), intrudes the Takomkane batholith and is considered by Soregaroli and Nelson (1976) to be responsible for molybdenite mineralization. An early breccia (Phase I Breccia, Soregaroli, 1968) with a matrix of comminuted rock flour and a clast suite dominated by the Takomkane batholith is spatially associated with molybdenite mineralization. Dikes of alkali basaltic composition, related to the Quaternary volcanic centre on Takomkane Mountain, cut all rock types related to the period of mineralization.

Molybdenite Mineralization

The mineralizing event at Boss Mountain, including both economic and sub-economic mineralization formed in two styles: (1) Veins; and (2) Phase II (Quartz matrix) Breccias.

Both types of mineralization describe partial annuli centred upon the Boss Mountain stock (Fig. 3). In both types, molybdenite with or without gangue minerals, occurs as either vein/fracture-fill in host rock (dominantly the Takomkane batholith), or in the matrix of pipe-shaped breccias of host rocks. Molybdenite rarely replaced any rock, with the local exception of biotitized mafic material in the breccia ore.

Vein Paragenesis and Classification

There are three principal vein types at Boss Mountain, defined

TABLE 1. Vein and breccia paragenesis at Boss Mountain, from oldest (i) to youngest (ix), based upon mapped cross-cutting relationships (Soregaroli, 1968; Macdonald, 1983)

Vein set	Breccia phase	Attitude Azimuth; Dip (°)	Texture	Essential mineralogy
i		040-060; vert	f.g., sugary	qtz \pm mo, py
ii		070-130; <30 NE/SW	f.g., sugary	qtz \pm py
iii		040-060; vert	f.g., sugary	qtz \pm mo, py
	Phase 1	irregular	c.r.f.m.	n.a.
iva, b		065; 60 NE/SW	f.g., ribbon	qtz-mo-py
v-a*	Quartz (Phase 2)*	v-a: variable; <40	c.g.	qtz-orth-py-mo
v-b		v-b: variable; <40	c.g.	qtz-orth-py-oxides-sulphides
v-c		v-c: 145; vert	c.g.	qtz-orth \pm py
vi		horizontal	c.g.	qtz-cc-orth
vii*		variable	f.g., ribbon	qtz-mo-py
viii		080; vert	f.g.	chl
ix		variable	f.g.	cc \pm py

Abbreviations: vertical

f.g.: fine-grained

c.r.f.m.: comminuted rock flour matrix

n.a.: not applicable

c.g.: coarse-grained

*: economically significant

qtz: quartz

mo: molybdenite

py: pyrite

orth: orthoclase

cc: calcite

chl: chlorite

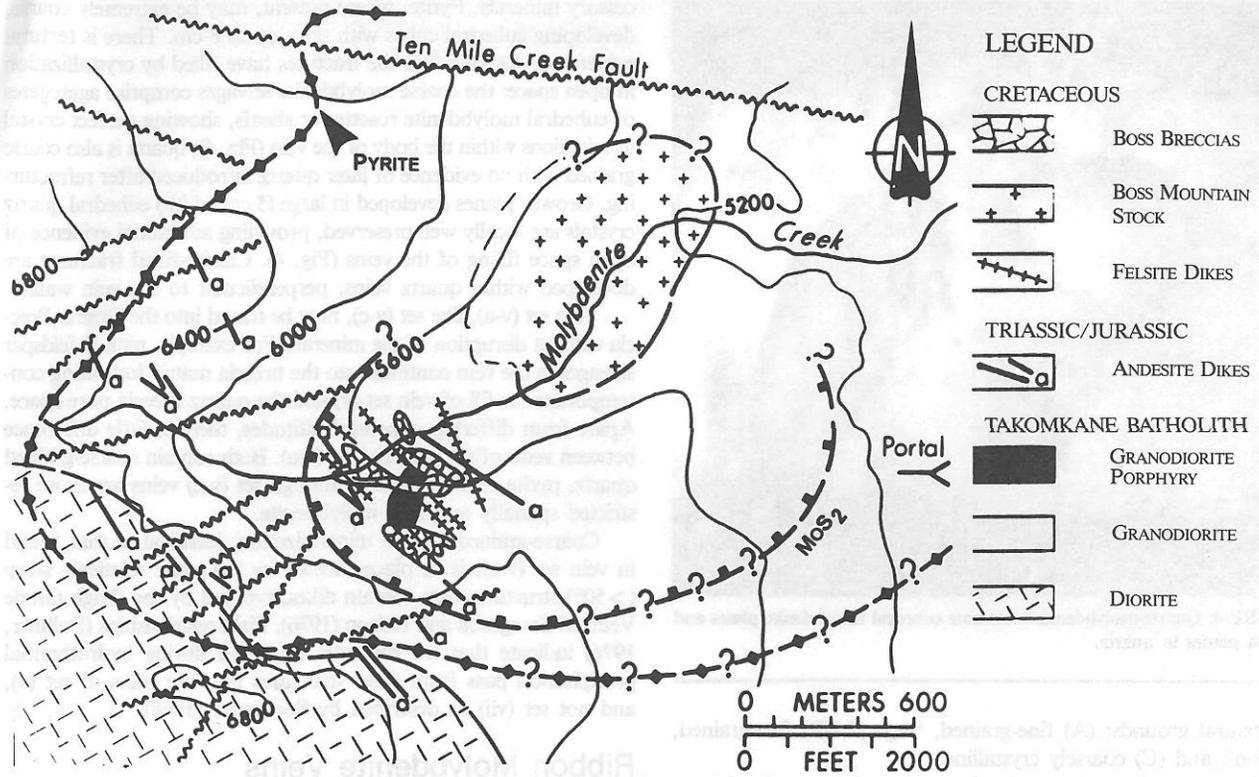


FIGURE 2. Geology of the Boss Mountain mine site (modified from Soregaroli and Nelson, 1976).

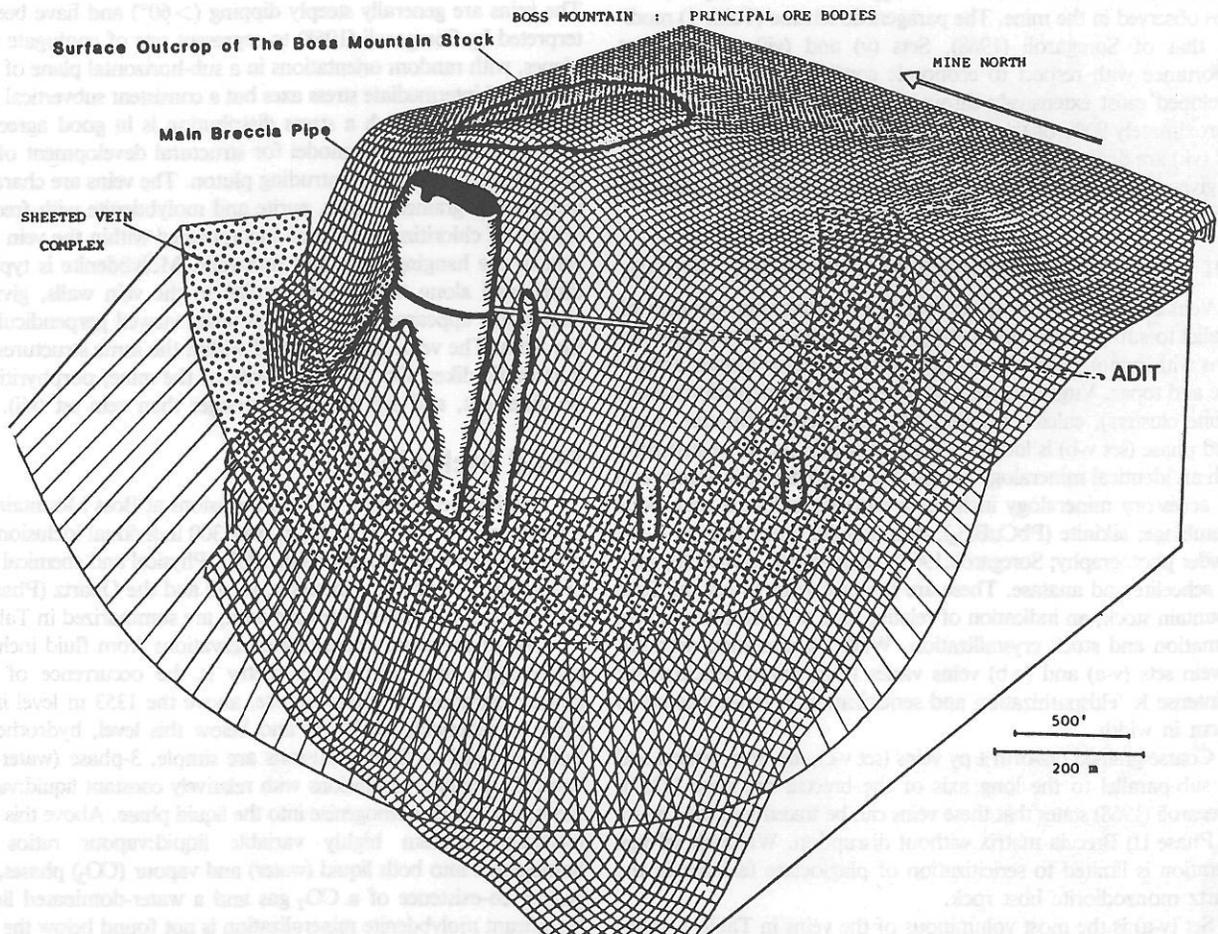


FIGURE 3. Isometric perspective projection of the breccia pipes (unshaded), outwardly-flaring sheeted vein complex (surface outcrop represented by dotted pattern) and surface of the Boss Mountain stock. Both veins and breccias describe partial annuli centred on the inferred apical region of the Boss Mountain stock.

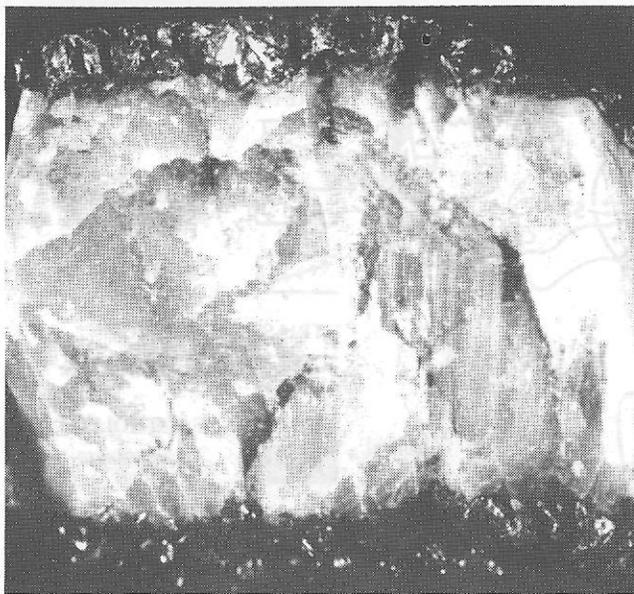


FIGURE 4. Quartz-molybdenite vein; note euhedral molybdenite plates and growth planes in quartz.

on textural grounds: (A) fine-grained, 'sugary'; (B) fine-grained, 'ribbon'; and (C) coarsely crystalline.

There are at least three sets of type A and two each of types B and C for a total of 7 vein sets or stages. Each set is defined by texture, attitude, essential mineralogy and cross-cutting relationships observed in the mine. The paragenetic scheme (Table 1) modifies that of Soregaroli (1968). Sets (v) and (vii) are of most importance with respect to economic considerations, as they are developed most extensively throughout the deposit and comprise approximately 90% of the vein and breccia material. Only sets (v) and (vii) are described here; descriptions of the remaining vein sets are given in Soregaroli (1968; 1975), Pollmer (1976) and Macdonald (1983).

Set (v): Coarse-grained Molybdenite Veins

Vein set (v-a) (Table 1) comprises a sheeted vein complex of parallel to sub-parallel, bifurcating, gently dipping qtz-orth-py-mo veins with minor sericite and rutile and very minor biotite, amphibole and topaz. Vugs are common, filled by zeolites (predominantly stilbite clusters), calcite, siderite, clay and, rarely, fluorite. A second phase (set v-b) is locally developed within the same structure, with an identical mineralogy except that molybdenite is absent and the accessory mineralogy includes a complex sulphide and oxide assemblage: aikinite (PbCuBiS_2), bismuthinite (identified by X-ray powder photography; Soregaroli, 1968), chalcopyrite, sphalerite, galena, scheelite and anatase. These are the first veins to cut the Boss Mountain stock, an indication of relative time of hydrothermal vein formation and stock crystallization. Wallrock alteration adjacent to vein sets (v-a) and (v-b) veins varies from minor sericitization to intense K-feldspathization and sericitization in envelopes up to 50 cm in width.

Coarse-grained qtz-orth \pm py veins (set v-c), are near vertical and are sub-parallel to the long axis of the breccia ore zone (325°). Soregaroli (1968) states that these veins can be traced into the Quartz (or Phase II) Breccia matrix without disruption. Wallrock selvage alteration is limited to sericitization of plagioclase feldspar in the quartz monzodiorite host rock.

Set (v-a) is the most voluminous of the veins in Table 1, cropping out within a partial annulus, the external diameter of which exceeds 1200 m (Fig. 3). Veins may be up to 1 m thick, but are typically between 5 cm and 10 cm thick, with coarse-grained molybdenite selvages up to 4 cm thick (average 1 cm). The remainder of the vein is filled by coarse-grained quartz and, locally, the ac-

cessory minerals. Pyrite, where present, may be extremely coarse, developing euhedral cubes with sides up to 8 cm. There is textural evidence to indicate that the fractures have filled by crystallization in open space: the coarse molybdenite selvages comprise aggregates of euhedral molybdenite rosettes or sheafs, showing perfect crystal terminations within the body of the vein (Fig. 4); quartz is also coarse grained with no evidence of later quartz introduced after refracturing. Growth planes developed in large (5 cm width) euhedral quartz crystals are locally well preserved, providing additional evidence of open space filling of the veins (Fig. 4). Calcite-filled fractures are developed within quartz veins, perpendicular to the vein walls.

Vein set (v-a), like set (v-c), may be traced into the Quartz Breccia without disruption of the minerals. For example, pink K-feldspar selvages in the vein continue into the breccia matrix indicating contemporaneous fill of vein set (v) and the quartz breccia pore space. Apart from differing structural attitudes, there is little difference between veins of set (v-c) and set (v-a). Both contain coarse-grained quartz, pyrite \pm K-feldspar, although set (v-c) veins are more restricted spatially and lack molybdenite.

Coarse-grained Qz-Mo mineralization, identical to that found in vein set (v-a), is in places hosted by the same relatively steep ($>50^\circ$) structures that contain dikes, typified by the 'High Grade Vein' of Soregaroli and Nelson (1976). Field relationships (Pollmer, 1976) indicate that the minerals deposited during hydrothermal precipitation pass from these structures into the veins of set (v), and not set (vii) as described by Soregaroli (1968).

Ribbon Molybdenite Veins

The qtz-mo ribbon veins of set (vii) are developed throughout the zone of mineralization, and locally contribute to the ore reserve. The veins are generally steeply dipping ($>60^\circ$) and have been interpreted by Soregaroli (1968) to represent sets of conjugate shear planes, with random orientations in a sub-horizontal plane of maximum and intermediate stress axes but a consistent subvertical minimum stress axis. Such a stress distribution is in good agreement with Anderson's (1936) model for structural development of ring dike structures above an intruding pluton. The veins are characterized by fine-grained quartz, pyrite and molybdenite with frequent screens of chloritized wall rock incorporated within the vein adjacent to the hanging walls and footwalls. Molybdenite is typically distributed along thin seams parallel to the vein walls, giving a ribbon-like appearance to the veins when viewed perpendicular to the walls. The veins may be found within the same structures that host mafic dikes. On the lower levels of the mine, porphyritic felsic dikes cut, and are therefore younger than vein set (vii).

Fluid Inclusions

Detailed petrography of fluid inclusions at Boss Mountain and microthermometric results from over 300 individual inclusions are presented elsewhere (Macdonald, 1983). Physical and chemical fluid properties of fluids in vein sets v, vi, vii and the Quartz (Phase II) breccia pipe, calculated from the data, are summarized in Table 2.

One of the more interesting observations from fluid inclusion petrography and microthermometry is the occurrence of CO_2 phase separation, or effervescence, above the 1353 m level in the mine (Macdonald, 1983). At and below this level, hydrothermal fluids trapped as fluid inclusions are simple, 3-phase (water- CO_2 liquid- CO_2 vapour) inclusions with relatively constant liquid:vapour ratios, and which homogenize into the liquid phase. Above this level, inclusions contain highly variable liquid:vapour ratios and homogenize into both liquid (water) and vapour (CO_2) phases, suggesting co-existence of a CO_2 gas and a water-dominated liquid. Significant molybdenite mineralization is not found below the 1353 m level.

One inference from this observation is that the ascending hydrothermal fluid responsible for molybdenite mineralization intersected the solvus within the $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}$ system at or around the 1353 m level in the mine, at which point CO_2 effervescence

TABLE 2. Physical and chemical properties of fluids responsible for molybdenite mineralization

Mole % H ₂ O	Mole % CO ₂	CO ₂ density (g/cm ₃)	Mole % NaCl eq. (Wt.% NaCl eq.)	Phase separation	Temperature (°C)	Pressure (bars)
94.5	3.6	0.35	1.9 (6)	Above 4440' (1353 m)	270-350, mean = 310	350

TABLE 3. Physical and chemical characteristics of some Mo deposits

Deposit	T (°C)	P (bars)	Salinity (% NaCl eq.)	CO ₂	Reference
Climax	395-415	<500	0.7-12	yes	Hall et al., 1974
Henderson	500-650	680-710	0-65	no	White et al., 1981
Buckingham	300-400	<300	4-12	yes	Blake et al., 1979
Hudson Bay Mtn.	300-400	215-270	0-12	yes	Bloom, 1982
Questa	360-450	275-450	5-12	yes	Bloom, 1982
Endako	350-400	?	5-14	no	Bloom, 1982
Trout Lake	370-400	1400-1700	2-16	yes	Linnen & Williams-Jones, 1990

took place. From the data of Frank (1977), the pressure at which phase separation takes place can be calculated, if mole % CO₂ and NaCl are known from other considerations (Table 2). At Boss Mountain, this pressure was 350 bars, which equates with a depth below surface of ~1300 m, assuming lithostatic pressure (Macdonald, 1983).

Relevance of Quartz-hosted Fluid Inclusions to Molybdenite

Throughout the preceding discussion of inferred physical and chemical conditions of the hydrothermal fluid responsible for mineralization at Boss Mountain, all fluid inclusions measured were in quartz. The validity of extrapolating physical and chemical inferences to molybdenite must be evaluated.

Within the scope of the analytical facilities available for this study, no single line of evidence indicates conclusively that the fluids responsible for quartz crystallization were identical to those from which molybdenite was deposited. A number of facts are, however, consistent with this interpretation:

1. One (typical) vein sample (B-79-193) consists of a 4 cm wide vein with 0.5 cm molybdenite selvages and 3 cm of vein quartz fill. Forty-four inclusions within the sample were investigated from the vein footwalls and hangingwalls and from the vein centre (Macdonald, 1983). In all three cases, fluid compositions (i.e. salinity, presence of CO₂ in some inclusions, etc.) and homogenization temperatures are similar, indicating that during vein filling, the fluid properties did not change appreciably, with the exception of a small number (4) of inclusions in the central part of the vein with homogenization temperatures less than 200°C.
2. In a few localities, molybdenite not only coats the vein walls as selvages, but is found within the vein as isolated plates that have crystallized on quartz. The sulphur isotopic compositions of molybdenite from vein hangingwalls, footwalls and centres are statistically indistinguishable (Macdonald, 1983) indicating that little occurred to alter the isotopic composition of the fluid between the time of vein wall and vein centre deposition, with no disturbance of the isotopic fractionation between fluid and crystallizing sulphide.
3. Similarly, hydrogen isotopes were analyzed from the fluid inclusions in molybdenite, pyrite and quartz; these are the same (Macdonald, 1983) implying a constant hydrogen isotopic composition of the fluid from which both quartz and molybdenite crystallized.
4. The euhedral crystal terminations of molybdenite plates that grew from vein walls into the vein centre are perfectly preserved, as opposed to being corroded. This implies that the fluid responsible for depositing quartz onto molybdenite was in chemical equilibrium with the sulphide. Disequilibrium would be indicated by corrosion of molybdenite euhedra.

Discussion and Conclusions

Temperatures and pressures of formation (estimated principally from fluid inclusion measurements) and fluid compositions for molybdenite deposits described in the literature are given in Table 3. The Boss Mountain data [approx. 350°C, 350 bars, 2-8 equiv. wt% NaCl (equivalent) and presence of CO₂] are very similar to those of most of these deposits, with the exception of Henderson. As a result of their work at Trout Lake (southeastern British Columbia) Linnen and Williams-Jones (1990) suggest that CO₂ is common in fluorine-deficient systems (e.g., Boss Mountain), in contrast with fluorine-rich systems. The temperature range over which the deposits are interpreted to have formed corresponds well with the theoretical calculations of Smith and Norman (1980) which indicate that molybdenum solubility decreases by two orders of magnitude between 350°C and 250°C. Carbon dioxide also appears to be a common occurrence in fluid inclusions associated with mineralization. Although few authors stress the point, it can be interpreted from their descriptions that CO₂ effervescence has accompanied mineralization at Climax (Hall et al., 1974) and Buckingham (Blake et al., 1979), where CO₂-bearing inclusions homogenize into both the liquid and vapour phases.

The wide variability in CO₂ volume percentages observed at Boss Mountain (Macdonald, 1983) has not been described from other deposits, although Kamilli and Ohmoto (1979) in a study of the Finlandia vein (Peru) found a wide variation in liquid:vapour ratios in inclusions trapped during H₂O boiling. Variability in volume percentages of the two components (CO₂ and H₂O) in the case of effervescence, or the two phases (liquid and vapour) in the case of boiling, can only occur if the vapour phase bubbles are smaller than the inclusion volume. Bubbles are only small in the vicinity of the location in which phase separation is initiated, above which their size increases by diffusion of the immiscible component into the bubble. This is additional evidence for the intimate association between the Boss Mountain mineralizing event and the onset of effervescence.

Investigation of the geology, mineralogy and quartz gangue-hosted fluid inclusions throughout the Boss Mountain deposit indicates that the initial molybdenum-bearing hydrothermal fluid (molar composition approximately 94% H₂O, 4% CO₂, 2% NaCl equivalent) entered the sheeted vein complex and breccia pipes, and intersected the H₂O-CO₂ solvus at approximately 350°C and 350 bars, inducing carbon dioxide phase separation. Within the mine, the phase separation and molybdenite mineralization are observed above the 1353 m elevation, interpreted to have been at a depth of 1300 m below paleo-surface during the ore-forming process.

Unless the spatial association of carbon dioxide effervescence and molybdenite precipitation from the hydrothermal fluid is coincidental, molybdenite precipitation may be triggered by a change in the CO₂ (or CO₃⁻) content of the solution, depending either upon complexing of the metal or pH of the fluid.

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