Porphyry Deposits of the Northwestern Cordillera of North America

Edited by
T.G. Schroeter
Geological Survey Branch
Ministry of Energy, Mines & Petroleum
Vancouver, British Columbia, Canada

Published for the Geological Society of CIM
as
SPECIAL VOLUME 46
by the
CANADIAN INSTITUTE OF MINING, METALLURGY AND PETROLEUM

Molybdenum mineralization in a fluorine-poor system: The Trout Lake stockwork deposit, southeastern British Columbia

R.L. LINNEN
Centre de Recherche sur la synthèse et chimie des minéraux, Centre National de recherche scientifique, Orléans, Cedex 2, France

A.E. WILLIAMS-JONES
Department of Geological Sciences, McGill University, Montreal, Quebec

C.H.B. LEITCH
Geological Survey of Canada, Mineral Resources Division, Vancouver, British Columbia

T.N. MACAULEY
Geological Consultant, Vancouver, British Columbia

ABSTRACT

The Trout Lake stockwork molybdenum deposit is temporally and spatially related to the emplacement of a late Cretaceous granodiorite-tonalite stock in southeastern British Columbia and contains an estimated 49 million tonnes grading 0.19% MoS_2. No metal zonation patterns are apparent, with the exception of peripheral tungsten skarn, and exploration was guided largely by geological interpretation. It is typical of the granodiorite, or fluorine-poor type of molybdenum deposit. Molybdenite is contained within a quartz-feldspar vein stockwork and coeval dissemination in igneous (and less commonly metasedimentary) hosts. In general, molybdenite is strongly associated with alkali feldspars, but in detail it is intimately associated with incipient muscovite replacement of albite and K-feldspar; veins that lack feldspars are also typically barren of molybdenite. These textures suggest that feldspathic alteration (and precipitation in veins) was an important precursor to mineralization, and the occurrence of similar textures elsewhere (e.g. Henderson) suggest that early feldspathic alteration is important to the genesis of molybdenum deposits in general. Molybdenite deposition at Trout Lake was preceded by contact metamorphism, skarn and potassic alteration, and was overprinted by muscovite-ankerite (phyllic) alteration. Only moderate temperature changes are recorded by the metamorphic and alteration mineral assemblages (350°C to 450°C); however, with time, fluids became increasingly more acidic and enriched in CO_2. In light of the intimate molybdenite-muscovite intergrowths, the decrease of pH probably exerted a major control on mineralization.

Introduction

Granite-hosted molybdenum deposits can be classified in terms of the composition of the related intrusion, e.g., the granodiorite and granite types of Mutschler et al. (1981), or the calc-alkaline, alkali-calcic, and alkalic types of Westra and Keith (1981). They have also been classified on the basis of their fluorine contents (Theodore and Menzie, 1984) with the fluorine-rich and -poor varieties roughly corresponding to granite- and granodiorite-type deposits, respectively. For economic reasons, most exploration and research has concentrated on the high-grade/large tonnage granite-type of deposit, exemplified by Climax. Fluorine-poor, granodiorite-type deposits are, however, the most common type in Canada and have been mined in the past (e.g., Endako). In this paper, the authors summarize the research that has been carried out on the fluorine-poor Trout Lake deposit (Boyle and Leitch, 1983; Linnen, 1985; Linnen and Williams-Jones, 1987; 1990) and use what has been learned to develop guidelines for the future exploration of fluorine-poor, granodiorite-type molybdenum deposits.

Location and History

The Trout Lake deposit is located in the Selkirk Mountains (50°38′N, 117°36′W; NTS 82K/12E), 60 km southeast of Revelstoke and 430 km east of Vancouver (Fig. 1). The deposit is exposed at 1450 m to 1520 m elevation along the northern ridge of Trout Mountain, with the ridge sloping 15° to 40° on either side. The first claims on the property were staked as the Lucky Boy and the Copper Chief in 1897 and 1901, respectively. A total of 414 tonnes of hand-sorted ore from small quartz veins was shipped from the Lucky Boy between 1901 and 1917, from which 2898 kg of silver and 121 tonnes of lead were recovered; a further 18 tonnes of tungsten (scheelite) ore was shipped in 1942 (Stevenson, 1943). Numerous other base and precious metal deposits are present in the district, many of which were exploited around the turn of the centrury.

Molybdenite was first reported in 1917, but it was not until 1969 that a subsidiary of Scurry Rainbow Oil Ltd. carried out a trenching and diamond drilling program. The property was optioned by Newmont Exploration of Canada in 1975. From 1976 to 1982, a Newmont/Esso Minerals Canada Ltd. joint venture project delineated the deposit by diamond drilling, initially from surface, and subsequently by ring drilling from an exploration adit. The pipe-like stockwork deposit extends from surface to a depth of greater than 1000 m and contains estimated reserves of 49 million tonnes grading 0.19% MoS_2 at a cutoff grade of 0.1% MoS_2 (revised from 50 million tonnes grading 0.23% MoS_2 quoted in Boyle and Leitch, 1983). The property has been inactive since 1982 and is now wholly owned by Newmont Mines Ltd.

Exploration Techniques

Exploration at Trout Lake has consisted of prospecting, geological mapping, trenching, soil, silt and rock geochemical surveys,

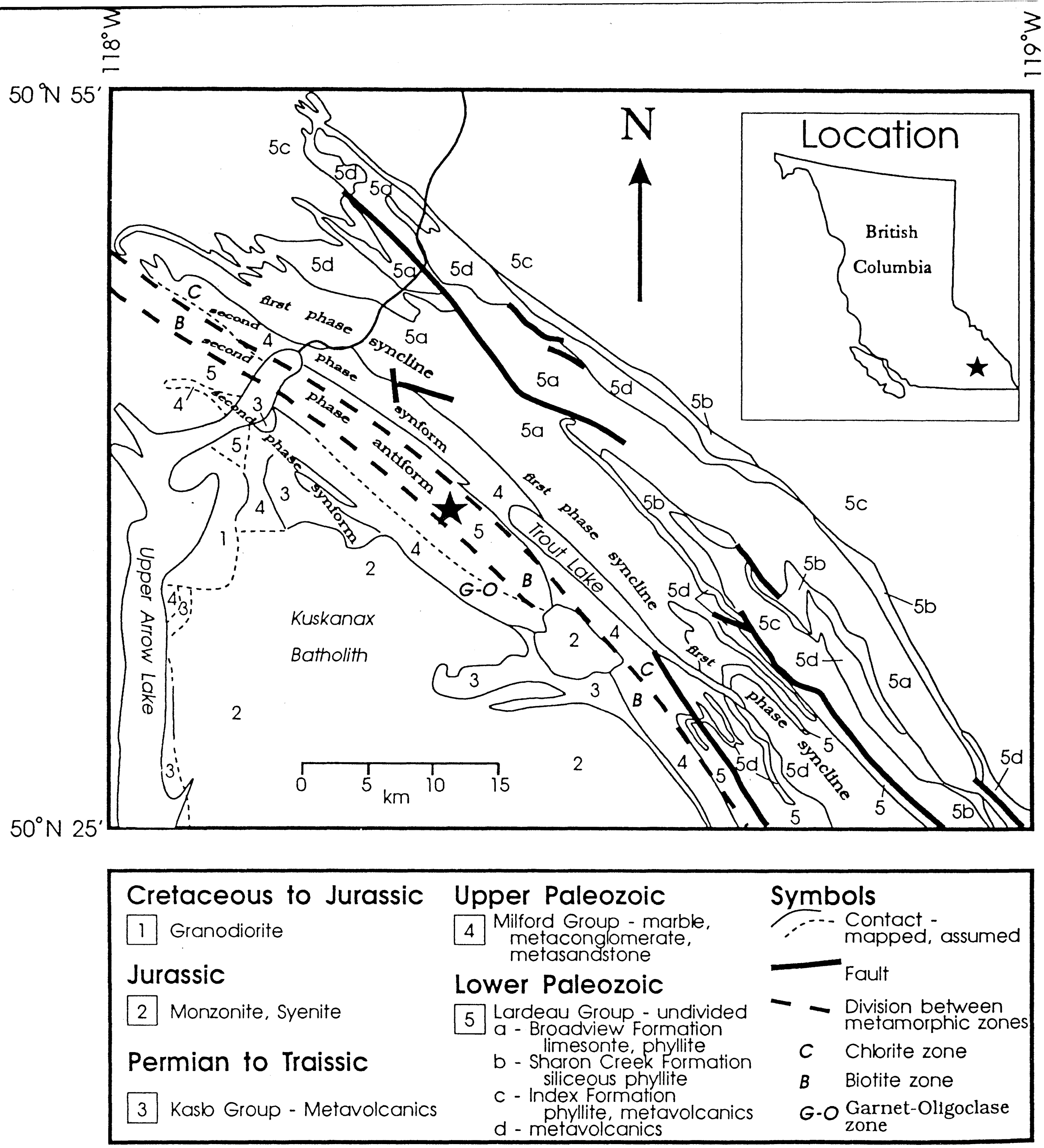

FIGURE 1. Regional geology modified after Read (1976) and Read and Brown (1981) and location of the Trout Lake deposit (star).

a magnetometer survey, diamond drilling (125 holes totaling 39 000 m), the driving of an adit (1300 m to reach the deposit and 700 m within it), bulk sampling, metallurgical testing, and engineering/feasibility/environmental studies. The natural exposure of molybdenite was limited to a few square metres and prospecting established the presence of stockwork molybdenum and tungsten skarn mineralization. The extent of the deposit at surface was subsequently delineated by a trenching program using a bulldozer. Sampling of B-horizon soils yielded a geochemical anomaly (defined by the 100 ppm Mo contour) extending 1000 m southeast from the mineralized zone along the side of the valley, as a result of glacial smearing (Fig. 2, Boyle and Leitch, 1983). The 20 ppm Mo contour (Fig. 2) indicates some downslope migration of molybdenum to the northeast and northwest, as well as lesser bedrock sources up the ridge to the south. A more extensive tungsten anomaly (500 m by 2000 m at the 120 ppm contour) overlaps with that of molybdenum and probably originates from the scheelite-bearing skarns adjacent to the molybdenum deposit (Boyle and Leitch, 1983).

The magnetometer survey showed only a few scattered anomalies, related to pyrrhotite contained in the skarns; the granodiorite stock could not be outlined magnetically. Consequently, exploration was guided almost entirely by geology and alteration.

Geological Setting

Regional Geology

The Trout Lake stock is a late Cretaceous post-kinematic, granodiorite-tonalite intrusion that was emplaced in the lower Paleozoic Lardeau Group of the Selkirk allochthon (76 Ma; Boyle and Leitch, 1983). The Lardeau Group, in the area surrounding the stock, consists of pelitic quartzite, marble, calcareous phyllite, calcareous quartzite and metavolcanic rocks, that underwent Jurassic regional metamorphism and deformation (Read and Brown, 1981). Major fold axes of the Jurassic deformation trend northwest-southeast, as do most of the faults in this area (Fig. 1). An important exception is the north-south trending Z Fault, along which the Trout Lake stock was intruded. Slickensides defined by molybdenite and mineralized veins cut by faults indicate that some faults, including the Z Fault, were active after (and possibly during) molybdenite deposition.

Contact Metamorphism

A contact metamorphic aureole, with dimensions of 1.2 km by 2 km at surface, was developed during the emplacement of the stock. This is most easily recognized in the calcareous lithologies, where the reaction 2 clinozoisite + CO_2 = 3 anorthite + calcite + H_2O has been used to define the outermost contact metamorphic isograd (Fig. 3). At surface, the highest grade contact metamorphic assemblage in the calc-silicate rocks consists of muscovite-chlorite-tremolite-clinozoisite-plagioclase-K-feldspar-quartz. The lack of contact metamorphic diopside and the presence of clinozoisite indicates that the temperature and the X_{CO_2} of the contact metamorphic fluid were low, <400°C and <0.05, respectively. The subsurface equivalent, calc-silicate hornfels, was closer to the magmatic heat-source (Fig. 4), and the assemblage biotite-tremolite-chlorite-plagioclase-quartz-titanite (K-feldspar and clinozoisite absent) records a higher temperature metamorphism, >440°C (Linnen and Williams-Jones, 1990).

Contact metamorphic isograds could not be established in the pelitic lithologies, however, the modal abundance of biotite decreases, and that of chlorite increases, with distance from the Trout Lake stock. The highest grade metamorphic pelitic units (quartz-biotite hornfels) also rarely contain remnant andalusite in the cores of muscovite porphyroblasts, indicating that the pressure during contact metamorphism was <3.8 kbar (Holdaway, 1971).

Intrusive Rocks

At surface the Trout Lake stock consists of only a few granodiorite and tonalite dikes over an area of 120 m by 300 m, but these dikes coalesce and thicken with depth and, at the adit level, the main granodiorite stock is 250 m across (Figs. 4 and 5). The intrusion is pipelike and records at least three pulses of magma: (1) light grey, early granodiorite consisting of equigranular (0.5 mm to 2 mm) plagioclase (40%), quartz (40%), K-feldspar (10%), biotite (10%) and rare hornblende; (2) dark grey, porphyritic tonalite, containing quartz 'eyes' and plagioclase phenocrysts (2 mm to 3 mm) in a matrix of plagioclase (45%), quartz (35%), biotite (15%) and K-feldspar (5%); and (3) late granodiorite which is compositionally similar to early granodiorite. The late granodiorite, and to a lesser extent tonalite, are characterized by abundant xenoliths of quartz-biotite hornfels and vein quartz. The late granodiorite occurs only as dikes <1 m thick, which are too small to be represented in Figures 4 and 5.

A close spatial and temporal relationship between the intrusion of granodiorite-tonalite and molybdenite precipitation is indicated by: (1) the fact that the contour of % MoS_2 closely follows the shape of the intrusion (Figs. 4 and 5); (2) mineralized quartz veins crosscut and are cut by granodiorite and tonalite dikes; and (3) late granodiorite, and to a lesser extent tonalite, contain xenoliths of vein quartz.

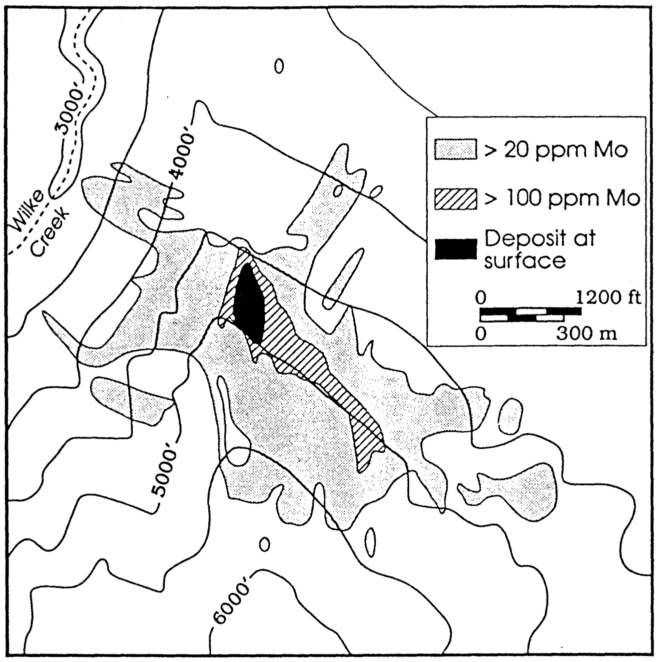

FIGURE 2. Molybdenum distribution in B-horizon soil samples, modified after Boyle and Leitch (1983).

Alteration

Four major types of alteration are recognized in the Trout Lake system: skarn and calc-silicate, potassic, quartz-feldspar-muscovite, and muscovite-ankerite. Although different stages of alteration have some minerals in common, each of the alteration types is temporally distinct. Skarn consists dominantly of clinopyroxene and garnet, occurs as a replacement of marble along faults adjacent to the Trout Lake stock (Fig. 6), and hosts minor scheelite. Tremolite ± clinozoisite locally replaces clinopyroxene and, in turn, is replaced by biotite and/or calcite, indicating that skarn predated potassic (biotite) alteration. Calc-silicate alteration (tremolite-clinozoisite) is locally observed to overprint hornfels throughout the deposit.

The manifestation of potassic alteration is dependent on the nature of the host rock. Biotite haloes are observed around quartz-albite ± K-feldspar veins which crosscut quartz-biotite and calc-silicate hornfels. Typically, the quartz-albite veins also contain pyrrhotite, minor chalcopyrite, and rarely, molybdenite. It is difficult to differentiate metasomatism and contact metamorphism in quartz-biotite and calc-silicate hornfels; both processes probably contributed to the biotite and K-feldspar contents of these units. However, plagioclase formed only during contact metamorphism (in both calc-silicate and quartz-biotite hornfels), and was later replaced by albite or K-feldspar, indicating that contact metamorphism and potassic alteration were distinct events.

Potassic alteration of the intrusive units is more cryptic. K-feldspar replacement of plagioclase is observed in thin section, but pervasive potassic alteration of granodiorite-tonalite is rare. In addition, it is difficult to distinguish K-feldspar formed during potassic alteration from that originating during subsequent quartz-feldspar-muscovite alteration (discussed below). These difficulties notwithstanding, a central core of potassic and "silicic" alteration (Fig. 7) was delineated from X-ray diffraction analysis of drill core pulps, which encouraged exploration at depth. It is important to note that the % quartz used to define the "silicic" alteration in Figure 7 includes vein quartz and, given the vein distribution in Figure 6, largely reflects the intensity of veining.

The highest grade molybdenite in the deposit is intimately associated with pervasive quartz-feldspar-muscovite alteration (consisting of three substages) that occurs in the centre of zones of intensive quartz veining (Figs. 6 and 7). The three substages are superposed

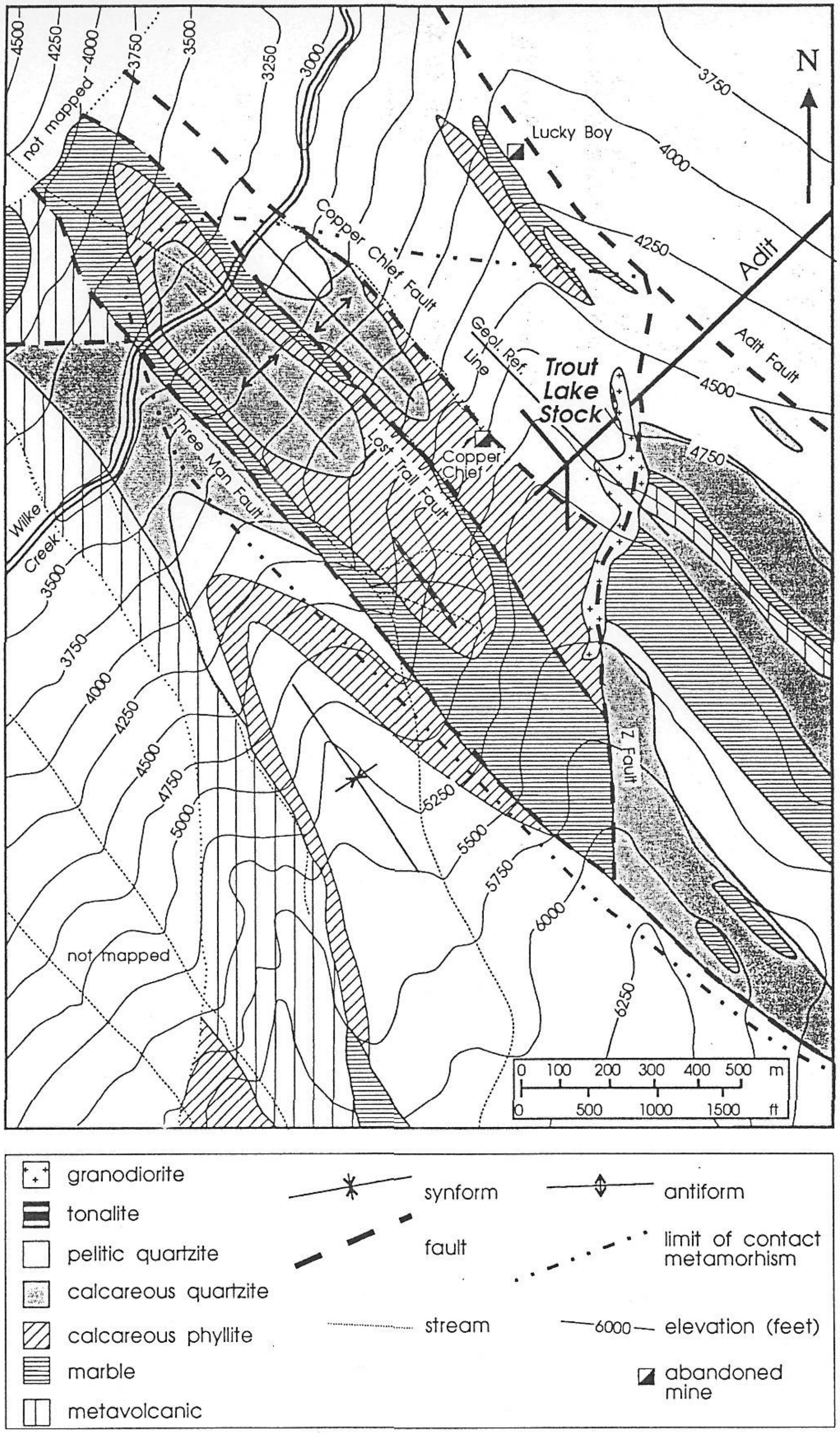

FIGURE 3. Surface geology of the Trout Lake area, modified after Linnen and Williams-Jones (1987).

and, where quartz-feldspar-muscovite alteration is pervasive, the wallrock is "bleached white" and clearly overprints potassic alteration in both intrusive and quartz-biotite hornfels units. Quartz-feldspar-muscovite alteration is thus a mappable and distinctive alteration type. Cross-cutting relationships also indicate that quartz-feldspar-muscovite alteration was followed by muscovite-ankerite (phyllic) alteration, in spite of muscovite being common to both alteration types. The three substages (exemplified in Fig. 8) are: early quartz and albite, as fine-grained flooding in intrusive hosts, or as relatively coarse-grained patches in quartz-biotite hornfels; an in-

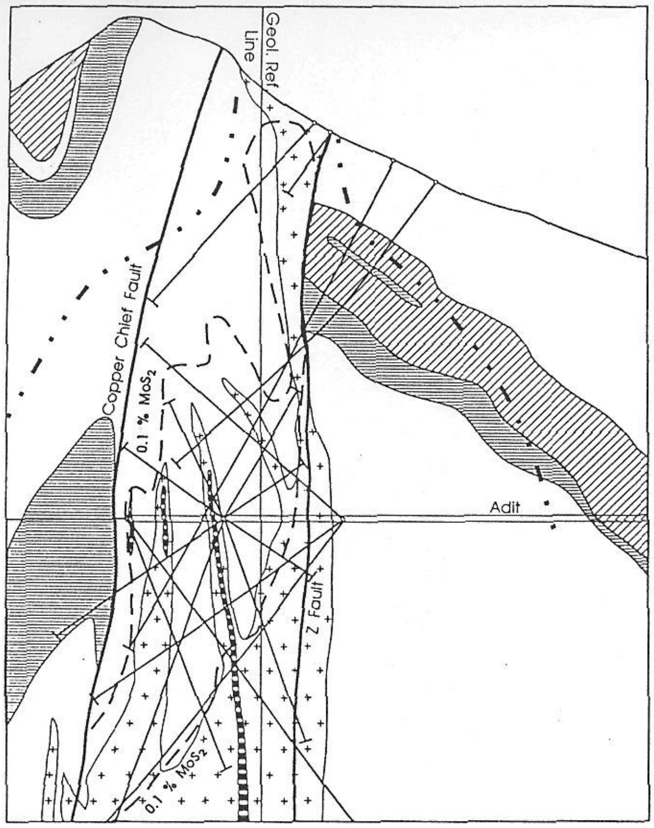

FIGURE 4. Cross-section along the adit of the Trout Lake deposit, modified after Boyle and Leitch (1983) and Linnen and Williams-Jones (1987). The dot-dash line represents the limit of the subsurface contact metamorphic facies and medium width solid lines drill hole locations; for other symbols see the legend on Figure 3.

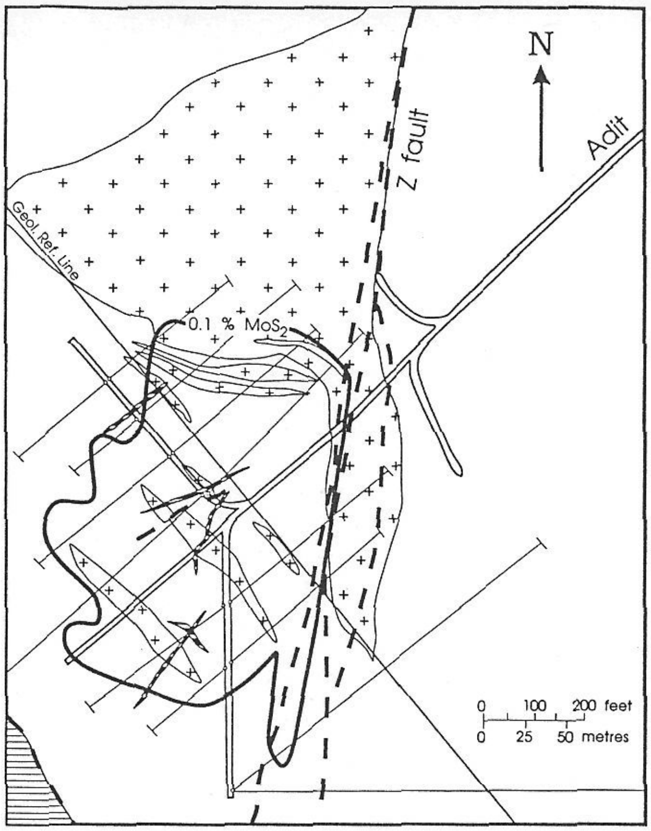

FIGURE 5. Plan view of the Trout Lake deposit at the adit level, modified after Boyle and Leitch (1983) and Linnen and Williams-Jones (1987). Medium width solid lines represent drill hole locations; for symbols see the legend on Figure 3.

termediate substage of replacement of albite by K-feldspar; and a final substage of incipient replacement of alkali feldspars by muscovite-calcite and successive replacement of biotite by chlorite and muscovite. Virtually all of the molybdenum mineralization in the deposit is associated with the final (muscovite) substage. Quartz-feldspar-muscovite alteration may be analogous to silicic alteration observed in other deposits; however, owing to the high abundance of feldspars it is not clear whether or not silica was added to the rock.

The youngest alteration, termed muscovite-ankerite, consists of quartz-muscovite-ankerite-pyrite ± K-feldspar. Veins with muscovite-ankerite haloes contain quartz and pyrite ± ankerite ± muscovite ± minor molybdenite. Vein feldspars, where present, are typically replaced by coarse-grained muscovite. This style of alteration is developed pervasively along faults, notably the Z Fault (Fig. 6), or as haloes around late, subhorizontal veins. It is readily distinguished from the muscovite-calcite substage of quartz-feldspar-muscovite alteration by the fact that it overprints the latter, the carbonate is ankerite (which oxidizes rapidly to a light brown colour), muscovite replacement of feldspar is pervasive rather than incipient, pyrite contents are much higher and the K-feldspar is microcline, whereas the K-feldspar from the preceding alteration stages is not visibly twinned (orthoclase?). Late chlorite-pyrite along fractures is also widespread, but this style of alteration is never pervasive.

Mineralization

Metal Association and Molybdenite Distribution

Trace-element analyses of drill core pulps indicate that weak tin enrichment (10 ppm to 20 ppm) may coincide with molybdenum and that anomalous tungsten (up to 300 ppm) occurs marginal to molybdenum. Rhenium, bismuth, antimony, silver, and gold were all near the limit of detection, and the few analyses of copper (up to 200 ppm), manganese and fluorine (300 ppm to 400 ppm), and uranium (up to 2 ppm) failed to show a discernable pattern. The gold content of the pyrrhotite-scheelite bearing skarns is generally near or below the 5 ppb detection limit; about 1% of the samples contained 100 ppb to 300 ppb.

Molybdenite is concentrated in a quartz vein stockwork and with pervasive quartz-feldspar-muscovite alteration, that extends for at least 1000 m vertically (using a 0.1% MoS_2 contour, Fig. 4) and at the adit level, covers an area of approximately 200 m by 300 m (Fig. 5). The highest grades (locally >1.0% MoS_2) occur in the zones of pervasive quartz-feldspar-muscovite alteration (Fig. 6), 'disseminated' in a microfracture network, accompanied by pyrrhotite, and to a lesser extent, pyrite and chalcopyrite. Molybdenite is invariably intergrown with muscovite or calcite, the latter having replaced K-feldspar, which in turn had replaced albite (as discussed above).

Stockwork mineralization consists of quartz veins ± K-feldspar ± albite ± muscovite ± molybdenite ± pyrrhotite ± pyrite ± chalcopyrite, generally 1 cm to 10 cm thick. The most important aspects of the distribution of the different types of veins (Linnen and Williams-Jones, 1987) are: (1) the intensity of veining (volume % veins in host rock) and the percentage of mineralized veins (compared to total number of veins) both increase toward the zones of pervasive quartz-feldspar-muscovite alteration; (2) the percentage of veins that contain feldspars, and of mineralized veins that contain feldspars, mimic this pattern; (3) the sequence of alteration within veins is identical to that of pervasive quartz-feldspar-muscovite alteration discussed above, i.e., K-feldspar replacement of albite, followed by muscovite-calcite replacement of the alkali feldspars (and an intimate calcite-muscovite-molybdenite association); (4) veins with moderate to abundant molybdenite cut veins with minor or

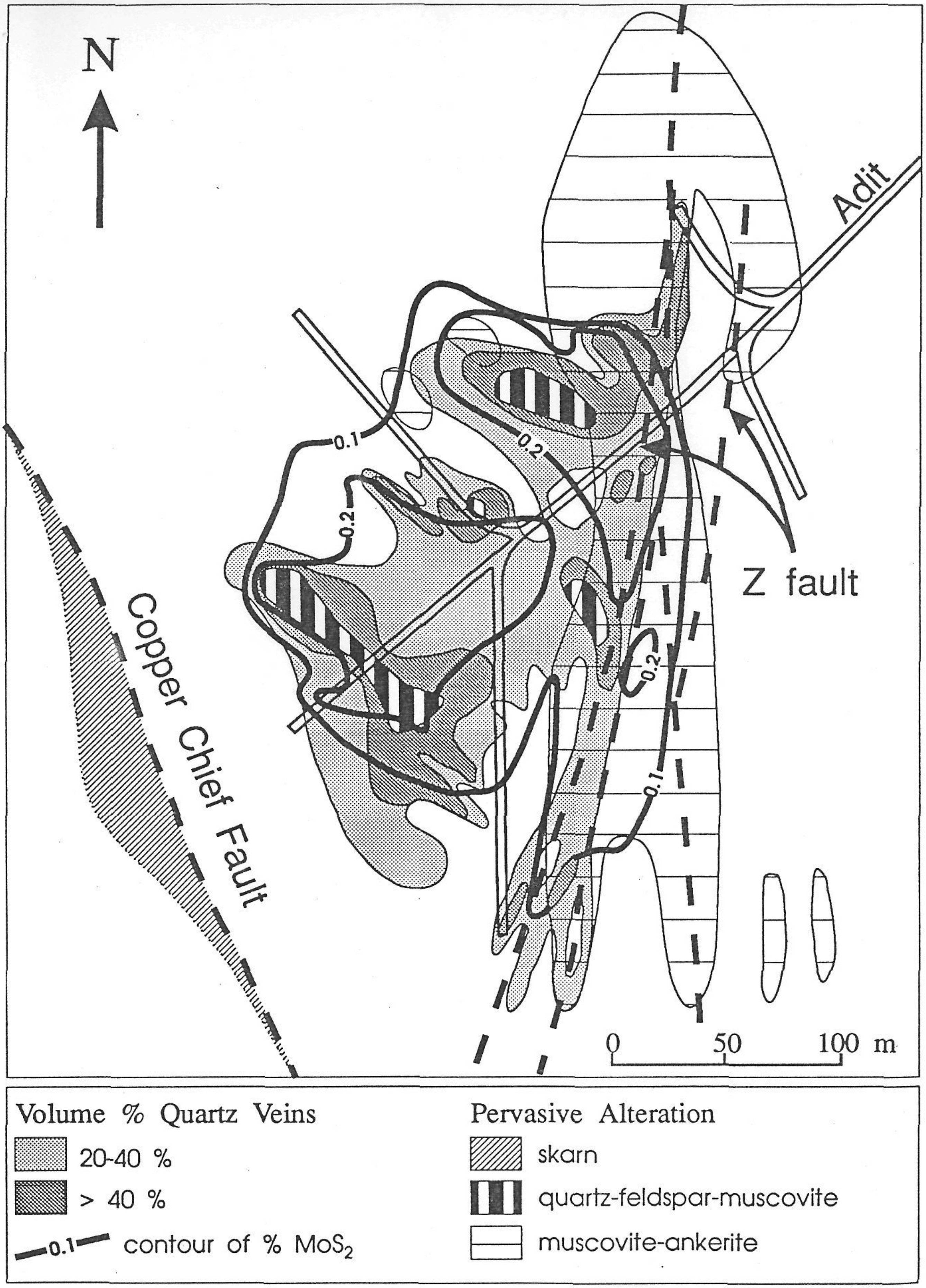

FIGURE 6. Plan view showing zones of pervasive alteration, volume percentage quartz veins and contours of MoS_2 grade, modified after Linnen and Williams-Jones (1990).

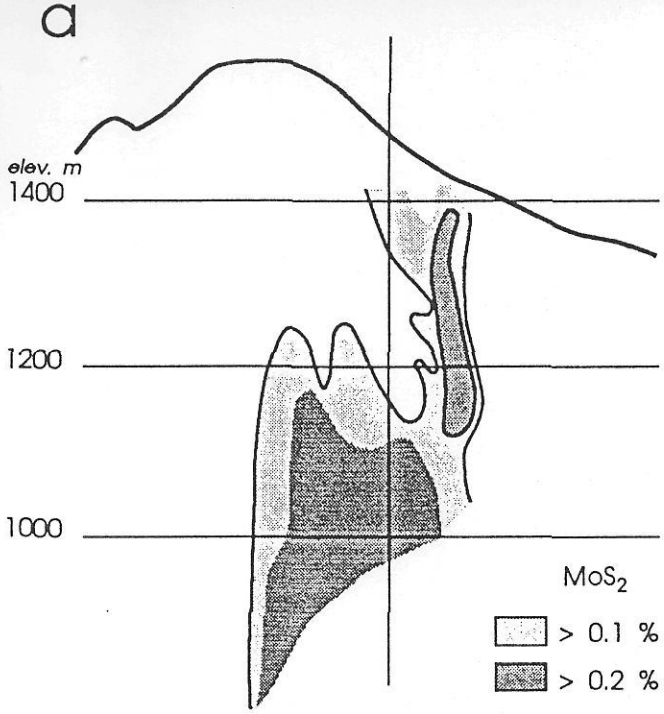

FIGURE 7a. Cross-section along the adit of the Trout Lake deposit showing results from drill core pulp analyses (containing wallrock and veins) — contours of MoS_2 grade. Modified after Boyle and Leitch (1983).

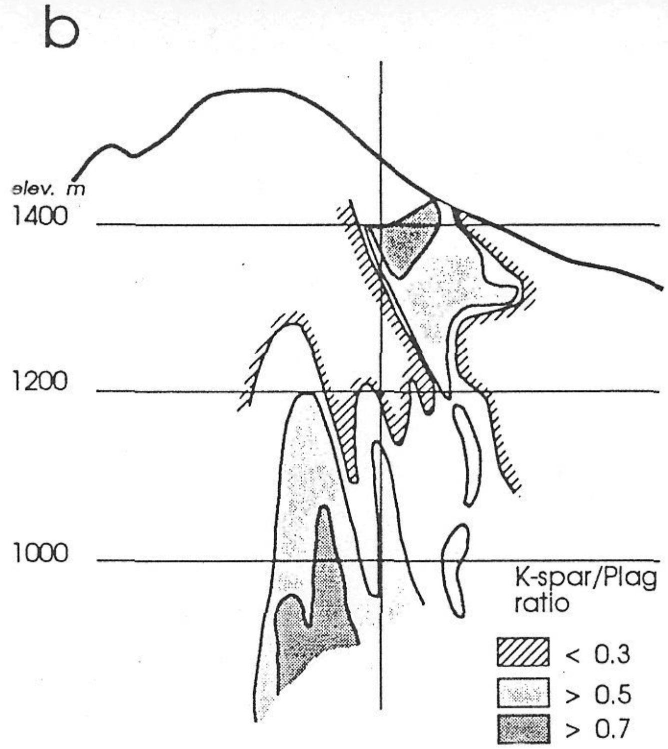

FIGURE 7b. Cross-section along the adit of the Trout Lake deposit showing results from drill core pulp analyses (containing wallrock and veins) — K-feldspar to plagioclase ratio. Modified after Boyle and Leitch (1983).

no molybdenite in the majority of intersections (indicating that the mineralization was relatively late in the evolution of the hydrothermal system); and (5) quartz-muscovite-pyrite veins are late, consistent with the fact that muscovite-ankerite alteration is late. It is evident from the cross-cutting relationships of veins, and in some cases from veins that were reopened several times, that the alkali feldspar-muscovite replacement sequence was highly repetitive and that each repetition was accompanied by a new pulse of molybdenite deposition.

Vein Orientations and Timing

Veins in the Trout Lake stockwork are dominantly in one of five orientations. Older veins (Trend 1) are parallel to the regional foliation (315°, subvertical). Orthogonal to this are Trend 2 veins (045°, subvertical) and late, subhorizontal Trend 4 veins. A conjugate set of subvertical, shear-related veins (Trends 3 and 5) at 005°E and 095° are also recognized. Linnen and Williams-Jones (1987) have interpreted the orthogonal fracture pattern to be a consequence of the release of stored elastic stresses. The close spatial and temporal relationships between veins and the Trout Lake stock indicate that hydraulic fracturing followed the emplacement of magma, and was caused either by expansion accompanying the release of orthomagmatic fluids, or by increased pressure associated with the heating of external (metamorphic or meteoric) fluids. The fact that stored elastic stress controlled the vein orientation, rather than stresses related to the intrusion, is compatible with the rapid uplift of the Kootenay arc from the middle Cretaceous to the early Tertiary (Archibald et al., 1983) and with the moderate depth of emplacement (approximately 6 km; Linnen and Williams-Jones, 1990) of the Trout Lake stock (in contrast, radial-concentric fracture patterns are invariably associated with hypabyssal intrusions).

Fluid Inclusions and Stable Isotopes

Two types of fluid inclusions are present in quartz at the Trout Lake deposit, aqueous and aqueous-carbonic (Linnen and Williams-Jones, 1990). Aqueous inclusions are the predominant type in potas-

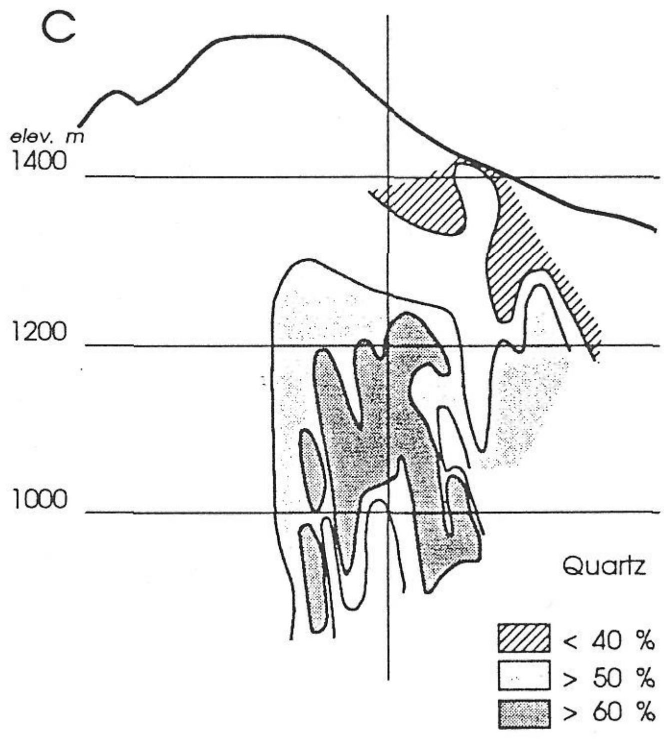

FIGURE 7c. Cross-section along the adit of the Trout Lake deposit showing results from drill core pulp analyses (containing wallrock and veins) — percentage of quartz. Modified after Boyle and Leitch (1983).

sically altered rocks, both inclusion types are abundant in mineralized veins and zones of pervasive quartz-feldspar-muscovite alteration, and muscovite-ankerite altered zones are characterized by aqueous-carbonic inclusions. The aqueous inclusions range in salinity from 2.2 wt% to 13.8 wt% NaCl eq. and homogenize to liquid at temperatures between 171°C and 369°C. The aqueous-

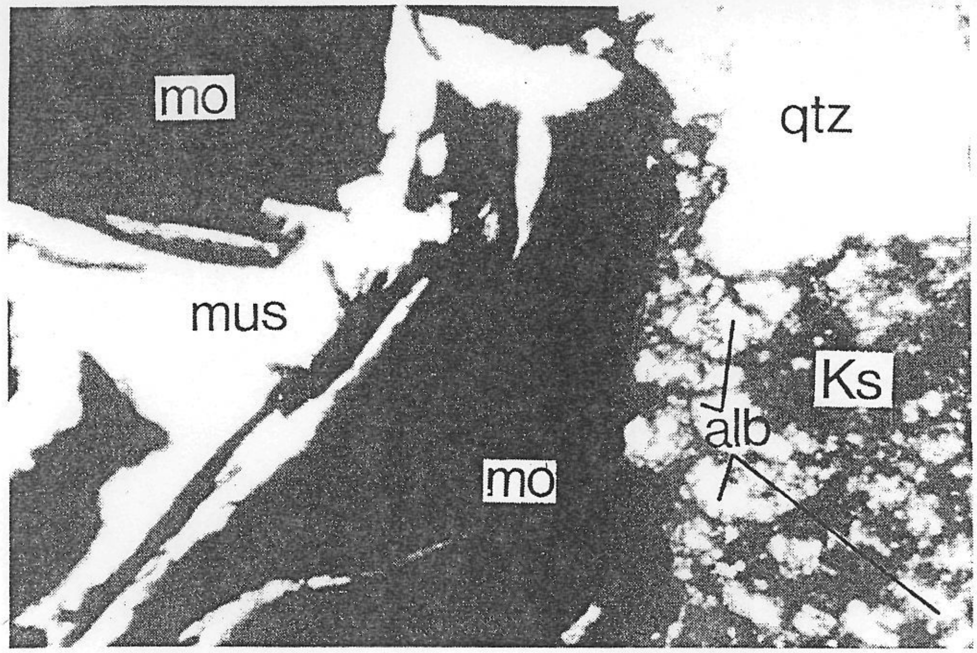

FIGURE 8. Plane polarized light photomicrograph showing the sequence of albite (white - alb) replaced by K-feldspar (medium grey - Ks) replaced by muscovite (mus) + molybdenite (mo). The K-feldspar was stained with sodium cobaltinitrite and the field of view is 0.85 mm across. Also present is a single grain of quartz (qtz).

carbonic inclusions contain approximately 10 mol% to 20 mol% CO_2, display a range of salinity similar to that of the aqueous inclusions and homogenize to liquid at 241°C to 336°C. The aqueous-carbonic inclusions hosted by veins in potassic and quartz-feldspar-muscovite altered rocks contain significant methane, X_{CH_4} up to 0.2, where X_{CH_4} is $CH_4/(CO_2+CH_4)$. By contrast, those hosted by veins in muscovite-ankerite altered rocks are essentially devoid of methane, indicating that the late fluids may have been more oxidizing.

The $\delta^{18}O$ values of quartz and muscovite range from 12.3 to 12.8 per mil and 9.6 to 10.0 per mil, respectively (Linnen and Williams-Jones, 1990). Temperatures determined from these data range from 370°C to 400°C, and the calculated $\delta^{18}O$ fluid composition ranges from 8.0 to 8.4 per mil. This composition is consistent with the involvement of magmatic fluids, modified groundwaters, or a combination of both.

Hydrothermal Evolution and Controls of Mineralization

The earliest hydrothermal event related to the emplacement of the Trout Lake deposit is contact metamorphism. The transfer of heat from the intrusion to the surrounding metasedimentary rocks may have initially been conductive, i.e., early andalusite porphyroblasts in the quartz-biotite schist may have formed during conductive heat transfer. However, isograds in calc-silicate lithologies are clustered distal from the intrusion, which is characteristic of an advective system (cf. Norton and Knight, 1977). The low X_{CO_2} of the contact metamorphic fluid (indicated by the stability of clinozoisite) implies infiltration of aqueous fluids, since conductive heat transfer would have resulted in metamorphic fluids of higher X_{CO_2} (cf. Greenwood, 1975). Temperature estimates from calc-silicate mineral assemblages, <400°C in the aureole defined at surface and approximately 440°C in the subsurface calc-silicate hornfels (Linnen and Williams-Jones, 1990), indicate that a large volume of country rock was heated to only moderate temperatures during the contact metamorphic event.

Contact metamorphism was followed by the formation of scheelite-bearing skarn, localized along fault intersections of marble, proximal to the Trout Lake stock. Clinopyroxene and garnet have a wide stability range, therefore the P, T and fluid composition of prograde skarn formation is poorly constrained. However, the retrograde skarn assemblage, which overprints prograde skarn but in turn is replaced by biotite, contains clinozoisite suggesting that the X_{CO_2} of this event was relatively low. Subsequent potassic alteration is characterized by low to moderately saline aqueous (CO_2-poor) fluid inclusions. The maximum temperature of potassic alteration, estimated by isochore extrapolation of these aqueous fluid inclusions to 2 kbar, is 460°C (Linnen and Williams-Jones, 1990).

Both aqueous and aqueous-carbonic fluid inclusions are abundant in quartz that occurs in mineralized veins or with quartz-feldspar-muscovite alteration and associated molybdenite. Temperature and pressure, estimated by oxygen isotope thermometry and isochore extrapolation, are 370°C to 400°C and 1400 bars to 1700 bars. The repetitive nature of quartz-feldspar-muscovite alteration (albite→K-feldspar→muscovite) and Mo deposition indicates either cyclic temperature fluctuation or cyclic decreases of the Na^+/K^+ and K^+/H^+ ratios of the mineralizing fluid(s).

Muscovite-ankerite alteration is the youngest alteration type recognized. The late timing of this alteration together with an abundance of pyrite indicate that it is equivalent to the phyllic alteration observed in many porphyry-type deposits. The late fluid evolution at Trout Lake differs from that of classic models of meteoric water influx by the fact that muscovite-ankerite alteration involved aqueous-carbonic fluids. Aqueous-carbonic fluid inclusions, with a composition of 10 mol% to 20 mol% CO_2, are the predominant type associated with this alteration. Using this fluid composition, and calc-silicate mineral stabilities, Linnen and Williams-Jones (1990) estimated that the temperature of muscovite-ankerite alteration was below 410°C, corroborated by an estimate of 384°C from oxygen isotope thermometry.

The thermometric estimates from mineral stabilities, fluid inclusions and oxygen isotopes indicate that contact metamorphism, potassic alteration, molybdenite deposition and associated quartz-feldspar-muscovite alteration and muscovite-ankerite alteration all occurred over a relatively narrow temperature range, 350°C to 450°C. It is, therefore, reasonable to argue that parameters other than temperature and pressure were responsible for the observed mineral assemblages. Likely candidates are pH and activity of

CO_2, which are used in Figure 9 to show the stabilities of different minerals. The assemblage plagioclase-biotite-quartz in hornfels indicates that the contact metamorphic fluid was relatively alkaline and that CO_2 activity was low ('1' in Fig. 9). It is evident from the presence of biotite and K-feldspar, that fluids remained alkaline, although possibly at higher CO_2 activity during potassic alteration. Biotite was not stable during molybdenite deposition, and its successive replacement by chlorite and muscovite can be explained by falling pH, as can muscovite replacement of K-feldspar ('2' and '3', respectively, Fig. 9). The stability of muscovite-calcite indicates that CO_2 activity was higher than in the preceding alteration substage. The presence of muscovite-ankerite-quartz in the final alteration stage implies an even greater CO_2 activity and possibly lower pH ('4' in Fig. 9). The fluid evolution as recorded by fluid inclusions (early aqueous to late aqueous-carbonic) is consistent with this proposed increase of CO_2 activity.

Molybdenum, whether in fluorine-rich, chlorine-rich, or CO_2-rich fluids, is most likely transported as an oxyacid complex. The most important parameters controlling molybdenite solubility are probably temperature, fS_2, fO_2 and pH. The relative effects of the latter three parameters can be understood by the simplistic reaction:

$$H^+ + HMoO_4^- + S_2 = MoS_2 + H_2O + 3/2\ O_2$$

Molybdenite precipitation by such a reaction is favoured by decreasing pH, fO_2, or fH_2O, or by increasing fS_2, and by a drop of temperature (although at magmatic to early subsolidus temperatures, molybdenite may have retrograde solubility). At Trout Lake, one or a combination of several of these factors could have controlled molybdenite deposition. The intimate association of molybdenite with incipient muscovite replacement of alkali feldspars, however, suggests that temperature and/or pH may have been the most important controls of mineralization (albeit the change in the valence of Mo, from +6 in bimolybdate to +4 in molybdenite, implies a redox reaction). Of greater importance to exploration, it is probable that early alkali feldspar alteration was an important precursor to mineralization because molybdenite is specifically linked to feldspar replacement (e.g., Fig. 8) and is not simply disseminated in veins.

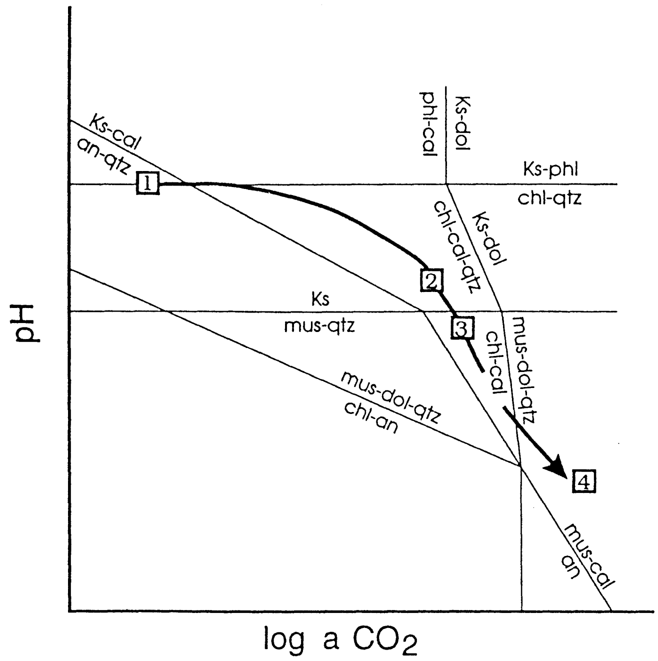

FIGURE 9. The stability of minerals in the system K_2O-CaO-MgO-SiO_2-Al_2O_3-H_2O-CO_2 as a function of pH and log activity of CO_2, modified after Linnen and Williams-Jones (1990). '1' represents conditions during contact metamorphism, '2' and '3' conditions during molybdenite depostion for the K-feldspar and muscovite stable substages of quartz-feldspar-muscovite alteration, respectively, and '4' late muscovite-ankerite alteration. The abbreviations are: an = anorthite, cal = calcite, chl = chlorite, dol = dolomite, Ks = K-feldspar, mus = muscovite, phl = phlogopite and qtz = quartz.

Implications of Fluorine-rich versus Fluorine-deficient Mineralization to Exploration

Contact Metamorphism

Contact metamorphism has commonly been regarded as an isochemical process and in cases of purely conductive heat transfer this is largely true. However, there is a growing body of evidence that recognizes an advective metamorphic-metasomatic stage prior to 'classic' alteration (distinct veins with haloes) may have implications to exploration, although this remains poorly understood. Some examples in which the relationships between contact metamorphism and mineralization have been documented are the George Lake Sb-W-Mo-Au-base metal deposit (Seal et al., 1988) and the Madeleine copper deposits (Williams-Jones et al., 1989). The latter is a particularly important example, because the contact metamorphic aureole developed largely by conductive heat transfer, but copper mineralization is located within a zone of advective metamorphism-metasomatism (van Bosse, 1985; van Bosse and Williams-Jones, 1988). Contact metamorphic-metasomatic aureoles are therefore potentially useful in the exploration of 'blind' deposits in analogous settings (post-kinematic intrusions).

Alteration and Mineralization

The alteration mineral assemblages associated with fluorine-rich and fluorine-deficient types of molybdenum deposits are, except with respect to the occurrence of fluorite and topaz, remarkably similar. This is in spite of large differences in the temperature of molybdenite deposition and the chemistry of the fluids: fluorine-rich type molybdenum deposits typically form at high temperatures (450°C to 750°C) from hypersaline fluids, whereas fluorine-deficient type mineralization is associated with low to moderately saline aqueous and aqueous-carbonic fluids, at moderate temperatures (250°C to 400°C).

The development of a central core dominated by alkali feldspar alteration is common to both deposit types. At Trout Lake the alkali feldspars consist of nearly pure albite (Ab_{96-100}) and orthoclase (Or_{92-98}). These compositions suggest that the feldspars underwent alkali exchange with fluids at temperatures lower than 400°C (Linnen, 1985). The alkali feldspars in fluorine-rich systems have retained a high albite component ($Or_{62}Ab_{38}$-$Or_{88}Ab_{12}$; Carten et al., 1988), reflecting a high temperature, late magmatic to early hydrothermal origin. The fact that micrographic quartz-K-feldspar intergrowths and unidirectional solidification textures are observed at Henderson, but are lacking at Trout Lake, is also very likely a consequence of the respective late magmatic to early hydrothermal and moderate temperature hydrothermal origins of the alkali feldspar alteration at the respective deposits.

It is significant that the pervasive quartz-feldspar-muscovite alteration at Trout Lake (Figs. 6 and 7) may be analogous to the pervasive silicic alteration observed at Henderson. But more importantly, molybdenite is intimately associated with incipient muscovite replacement of alkali feldspars at the two deposits (and at virtually all other fluorine-rich and fluorine-deficient deposits), suggesting that molybdenite precipitates by a similar process in both fluorine-rich and fluorine-deficient environments. The presence of an alkali feldspar alteration core is therefore probably of critical importance for the deposition of molybdenum and the delineation of such zones is a useful guide in exploration (Boyle and Leitch, 1983).

One of the greatest divergences between fluorine-rich and fluorine-deficient deposits is that of metal association. While fluorine, tin and rare-earth elements may be useful pathfinder elements for fluorine-rich deposits, in fluorine-deficient deposits, molybdenum is the only element that has been demonstrated to be useful in geochemical exploration.

Economics

Drill-indicated, geological reserves for the four zones comprising the Trout Lake deposit are estimated at 48 700 000 tonnes grading 0.193% MoS_2 at the 0.10% cutoff, or 11 700 000 tonnes grading 0.362% MoS_2 at the 0.20% cutoff, calculated manually on sections 30 m apart. In bulk sampling of 128 drift rounds having a pilot diamond drill hole for comparison, bulk sample grades varied from 85% to 137% of drill hole grades, and averaged slightly greater than the grades of the drill hole. Continuity of mineralization at 0.10% to 0.20% MoS_2 is good; at higher cutoff grades it is more difficult to estimate tonnages, because the estimation involves fewer drill holes and fewer samples. The potential for increasing reserves lies mainly at depth.

A mining study based on reserves at the 0.20% cutoff envisaged open stoping with delayed cemented backfill, utilizing the existing adit as a haulage level. The adit intersects the deposit at its midpoint, 500 m below surface. Further studies aimed at extracting higher grades with more selective mining methods have been recommended. Initial metallurgical testing of drill core indicated a 90% recovery of molybdenite in a 90% to 92% MoS_2 concentrate. Tests on some adit samples showed concentrate grade to decrease significantly as recovery increased. This was attributed to coatings of molybdenite on gangue particles in the silica-rich metasedimentary rocks that surround the stock; recoveries in other rock types were satisfactory.

Conclusions

The Trout Lake deposit is a typical granodiorite, or fluorine-deficient type of molybdenum deposit. Molybdenum is virtually the only metal present in significant quantities at Trout Lake, thus analyses of other metals or fluorine is unlikely to be useful in the exploration of this type of deposit. Studies of alteration, however, indicate that a precursor alkali feldspar stage is important in both fluorine-rich and fluorine-deficient types of molybdenum deposits and the recognition of this alteration (e.g., Fig. 6b) can be an important exploration guide. Development of the Trout Lake deposit will require expanded markets and higher prices of molybdenum. Lastly, the identification of advective contact metamorphic aureoles has a potential application to the exploration of a wide variety of metals associated with granite.

Acknowledgments

Financial assistance for the research was provided by Newmont Exploration of Canada Ltd. and Esso Minerals Canada Ltd. and a Natural Science Engineering Research Council grant (A.E.W.-J.). The manuscript benefitted from reviews by R.V. Kirkham and J.R. Woodcock.

REFERENCES

ARCHIBALD, D.A., GLOVER, J.K., PRICE, R.A., FARRAR, E. and CARMICHAEL D.M., 1983. Geochronology and tectonic implications of magmatism and metamorphism, southern Kootenay arc and neighbouring regions, southeastern British Columbia. Part I: Jurassic to mid Cretaceous. Canadian Journal of Earth Sciences, 20, p. 1891-1913.

BOYLE, H.C. and LEITCH, C.H.B., 1983. Geology of the Trout Lake molybdenum deposit, B.C. Canadian Institute of Mining and Metallurgy, Bulletin, 76, No. 849, p. 115-124.

CARTEN, R.B., GERAGHTY, E.P., WALKER, B.M. and SHANNON, J.R., 1988. Cyclic development of igneous features and their relationship to high-temperature hydrothermal features in the Henderson porphyry molybdenum deposit, Colorado. Economic Geology, 83, p. 266-296.

GREENWOOD, H.J., 1975. Buffering of pore fluids by metamorphic reactions. American Journal of Science, 275, p. 573-593.

HOLDAWAY, M. J. 1971. Stability of andalusite and the aluminum silicate phase diagram. American Journal of Science, 271, p. 97-131.

LINNEN, R.L., 1985. Contact metamorphism, wallrock alteration, and molybdenite mineralization at the Trout Lake stockwork deposit, southeastern British Columbia. Unpublished M.Sc. thesis, McGill University, Montreal, Quebec, 220 p.

LINNEN, R.L. and WILLIAMS-JONES, A.E., 1987. Tectonic control of quartz vein orientations at the Trout Lake stockwork molybdenum deposit, southeastern British Columbia: Implications for metallogeny in the Kootenay arc. Economic Geology, 82, p. 1283-1293.

LINNEN, R.L. and WILLIAMS-JONES, A.E., 1990. Evolution of aqueous-carbonic fluids during contact metamorphism, wallrock alteration, and molybdenite deposition at Trout Lake, British Columbia. Economic Geology, 85, p. 1840-1856.

MUTSCHLER, F.E., WRIGHT, E.G., LUDINGTON, S. and ABBOT, J.T., 1981. Granite molybdenite systems. Economic Geology, 76, p. 874-897.

NORTON, D. and KNIGHT, J., 1977. Transport phenomena in hydrothermal systems: Cooling plutons. American Journal of Science, 277, p. 937-981.

READ, P.B., 1976. Lardeau map-area (82K west half), British Columbia. Geological Survey of Canada, Paper 76-1A, p. 95-96.

READ, P.B. and BROWN, R.L., 1981. Columbia river fault zone: southeastern margin of the Shuswap and Monashee complexes, southern British Columbia. Canadian Journal of Earth Sciences, 18, p. 1127-1145.

SEAL, R.H. II, CLARK, A.H. and MORRISSY, C.J., 1988. Lake George, southwestern New Brunswick: a Silurian, multi-stage, polymetallic (Sb-W-Mo-Au-base metal) hydrothermal centre. *In* Recent Advances in the Geology of Granite-Related Mineral Deposits. *Edited by* R.P. Taylor and D.F. Strong. Canadian Institute of Mining and Metallurgy, Special Volume 39, p. 252-264.

STEVENSON, J.S., 1943. Tungsten deposits of British Columbia. British Columbia Department of Mines and Petroleum Resources, Bulletin 10, p. 130-133.

THEODORE, T.G. and MENZIE, W.D., 1984. Fluorine-deficient porphyry molybdenum deposits in the western North America Cordillera. *In* International Association on the Genesis of Ore Deposits. *Edited by* T.V. Janelidze and A.G. Tvalchrelidze. Proceedings of the Sixth Quadrennial Symposium, p. 463-470.

WESTRA, G. and KEITH, S.B., 1981. Classification and genesis of stockwork molybdenum deposits. Economic Geology, 76, p. 844-873.

WILLIAMS-JONES, A.E., SAMSON, I.M. and LINNEN, R.L., 1989. Fluid evolution and its role in the genesis of the granite-related Madeleine copper deposit, Gaspé, Quebec. Economic Geology, 84, p. 1515-1524.

VAN BOSSE, J.Y., 1985. Metamorphism and alteration in the thermal aureole of the McGerrigle Mountain pluton, Gaspé, Quebec. Unpublished M.Sc. thesis, McGill University, Montreal, Quebec, 185 p.

VAN BOSSE, J.Y. and WILLIAMS-JONES, A.E., 1988. Chemographic relationships of biotite and cordierite in the McGerrigle thermal aureole, Gaspé, Quebec. Journal of Metamorphic Geology, 6, p. 65-75.