METAMORPHISM OF ARSENOPYRITE – PYRITE – SPHALERITE – PYRRHOTITE LENSES, WESTERN CAPE BRETON ISLAND, NOVA SCOTIA*

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ABSTRACT

Polymetallic sulfide lenses occur in Ordovician–Silurian sequences of clastic and volcanic rocks of the western Cape Breton Highlands, Nova Scotia. The rocks have been affected by thrusting and metamorphism during late Silurian to Devonian Acadian deformation. The sulfides occur as highly sheared and recrystallized lenses concordant to bedding. Mineral compositions of equilibrium sphalerite – arsenopyrite – pyrrhotite – pyrite intergrowths provide a sliding-scale indicator of P–T–$f(S_2)$ variations during metamorphism. The arsenopyrite contains between 33 to 29 atom % As, a range reflecting recrystallization within a changing thermal regime, at temperatures between 510° and 300°C. Pyrrhotite with up to 47.3 atom % Fe is recorded; however, most of the pyrrhotite is relatively sulfur-rich, likely owing to low-temperature inversion or partial oxidation. The dominant composition of sphalerite, between 13–14 mol % FeS, indicates intermediate- to high-pressure conditions. Pressure estimates of 5.5 to 6.9 kilobars are consistent with upper-greenschist metamorphic assemblages found in the surrounding rocks. Decreasing fugacity of sulfur accompanied retrogression in the sulfide lenses as a consequence of the buffering capacity of the coexisting pyrite and pyrrhotite.

Keywords: sphalerite, geobarometer, arsenopyrite, geothermometer, pyrrhotite, retrogression, shear, volcanogenic, syngenetic, epigenetic, Cape Breton Island, Nova Scotia.

SOMMAIRE

Des lentilles sulfurées polymétalliques sont présentes dans des séquences clastiques et volcaniques ordoviciennes-siluriennes des Hautes Terres occidentales du Cap Breton, en Nouvelle-Ecosse. Les roches ont été remaniées par chevauchement et métamorphisme durant la déformation liée à l'orogenèse acadienne, au Siluro-Dévonien. Les lentilles de sulfures, sont concordantes et ont été fortement cisaillées et recristallisées. Les compositions des minéraux sphalérite – arsénopyrite – pyrrhotite – pyrite en intercroissances à l'équilibre servent d'indicateurs des variations de P–T–$f(S_2)$ durant le métamorphisme. L'arsénopyrite contient de 33 à 29% (atomique) de As, indiquant une recristallisation dans un régime thermique variable, à des températures entre 510° et 300°C. La pyrrhotite peut contenir jusqu'à 47.3% de Fe, mais elle est en général enrichie en S, possiblement à cause d'inversions à basse température, ou à une oxydation partielle. La composition de la sphalérite varie principalement entre 13–14% (molaire) de FeS, indiquant des conditions de moyenne à haute pression. Nous estimons une pression de 5.5 à 6.9 kilobars, ce qui concorde bien avec les assemblages métamorphiques du faciès schiste vert supérieur dans les roches encaissantes. Une fugacité de S décroissante accompagnant la rétrogression métamorphique des sulfures résulte de la capacité de pyrite et pyrrhotite coexistantes d'agir comme tampon.

Mots-clés: sphalérite, géobaromètre, arsénopyrite, géothermomètre, pyrrhotite, rétrogression, cisaillement, volcanogène, syngénétique, epigénétique, Île du Cap Breton, Nouvelle-Ecosse.

INTRODUCTION

The sphalerite geobarometer has received considerable attention owing to 1) its potential in interpreting metamorphosed sulfide assemblages, and 2) the simple chemistry and refractory nature of sphalerite (Scott & Barnes 1971, Scott 1973, Hutchison & Scott 1981, Bryndzia et al. 1988, 1990, Toulmin et al. 1991, Lusk et al. 1993). Experimental results have demonstrated that temperature is secondary to pressure in controlling the composition of sphalerite in equilibrium with pyrrhotite and pyrite. However, thermodynamic calculations (Toulmin et al. 1991) reveal that temperature may have a significant effect on the iron content of sphalerite in equilibrium with pyrrhotite and pyrite; thus it must be taken into account if accurate determinations of pressure are to be made.

As with sphalerite, arsenopyrite is a relatively refractory sulfide that exhibits appreciable solid-solution sensitive to temperature and pressure (Clark 1960a, b, Barton 1970, Kretschmar & Scott 1976, Sharp et al. 1985); its composition provides geothermometric information under conditions of the greenschist and lower amphibolite facies (Sharp et al. 1985). Because of the existing body of experimental data on sphalerite and on arsenopyrite, as well as on the pyrite–pyrrhotite solvus (Toulmin & Barton 1964), the assemblage sphalerite – arsenopyrite – pyrite – pyrrhotite can be an indicator of metamorphic conditions.

In this paper, we present petrographic and compositional data on sphalerite, pyrrhotite and arsenopyrite from sulfide lenses that have been sheared as a result of Acadian deformation in the Cheticamp area, western Cape Breton Highlands (Fig. 1). Peak conditions of metamorphism for amphibolite-grade rocks in the region are well established on the basis of silicate mineralogy (Currie 1987, Plint & Jamieson 1989);
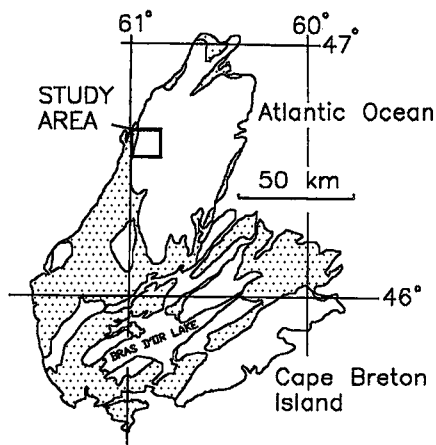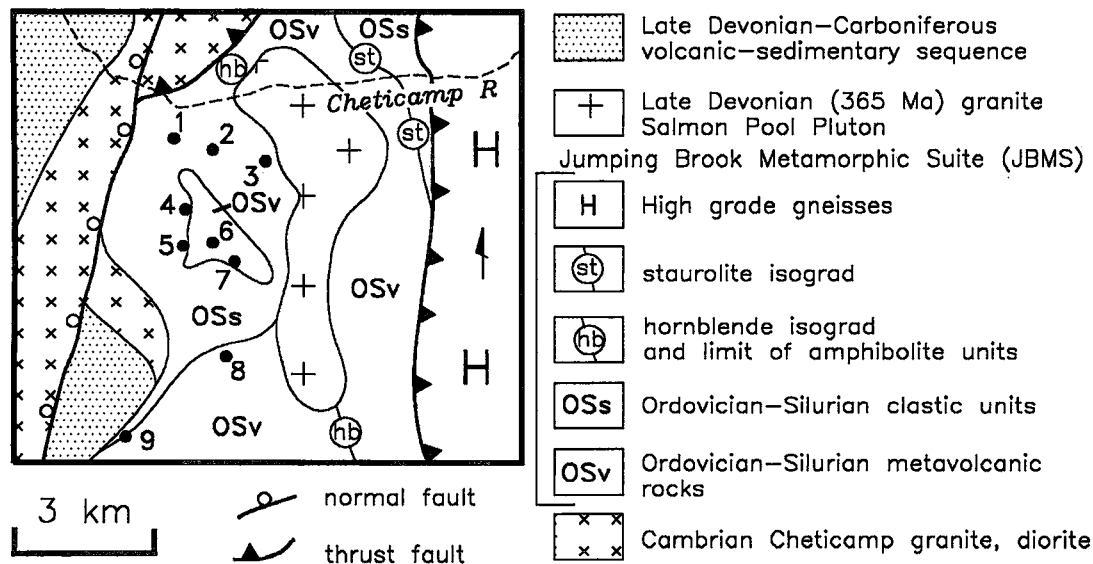

FIG. 1. Location and geology of the study area showing distribution of the mineral occurrences: (1) Galena Mine, (2) Core Shack, (3) Silver Cliff, (4) Iron Cap, (5) Mountain Top, (6) Road 1, (7) Road 2, (8) Campbell, (9) Fisset Brook. Modified from Jamieson et al. (1990) and Lynch & Tremblay (1992).

however, greenschist-grade assemblages are less well characterized in terms of their metamorphic conditions. Below, we present estimates of P, T, and sulfur fugacity appropriate for the upper-greenschist-grade metamorphic rocks based on the arsenopyrite geothermometer and sphalerite geobarometer. These estimates provide insight into the processes of mineralization and into the metamorphic evolution of the region.

GEOLOGICAL SETTING

The Cambrian Cheticamp granite is the oldest map-unit exposed in the study area (Fig. 1). It forms an elongate body, extending about 25 km from north to south, and is in fault contact with adjacent units. Late Ordovician to early Silurian metavolcanic and clastic metasediments of the Jumping Brook metamorphic suite (JBMS) host the polymetallic sulfide lenses described here (Jamieson *et al.* 1990) (Fig. 1). The JBMS includes a lower unit containing mafic to intermediate metavolcanic rocks and metadiorite, which passes upward into coarse-grained siliciclastic and arkosic metasedimentary rocks, quartz-pebble conglomerate, quartzite, wacke, and rare thin felsic volcanic horizons. Rocks that correlate with the JBMS are widely distributed throughout much of the Highlands (Jamieson *et al.* 1990, Lynch & Tremblay 1992), and elsewhere within the Appalachian orogen (Barr & Jamieson 1991).

High-grade gneiss occurs east of the mineralized JBMS (Jamieson *et al.* 1986, Currie 1987) (Fig. 1). Available petrological and geochronological data suggest that peak conditions of metamorphism of the gneissic rocks reached 700°–750°C at 8–10 kbar during late Silurian to early Devonian Acadian deformation (Plint & Jamieson 1989). Metamorphic grade in the study area increases from west to east toward the gneissic rocks (Fig. 1), and ranges from greenschist to amphibolite facies (Currie 1987, Plint & Jamieson 1989). Thickening of the JBMS, marked by the structural repetition of clastic and volcanic units, is the result of an early phase of thrusting and imbrication (Lynch & Tremblay 1992). A steep-angle reverse fault cross-cuts the imbricate stack and juxtaposes the high-grade gneissic rocks against the clastic and volcanic units (Craw 1984, Lynch & Tremblay 1992). The district has been subdivided into low-, medium-, and high-grade belts, characterized by the presence of chloritoid, staurolite and kyanite, respectively (Craw 1984, Plint & Jamieson 1989). The zonation cross-cuts the earlier system of thrusts, and is related to the thrust emplacement of the high-temperature gneissic rocks against the cooler units of the footwall.

Peak conditions of metamorphism within the low-grade belt of the JBMS, which contains the sulfide lenses, reached the upper greenschist facies. Metamorphic assemblages include, in varying propor-

tions, chlorite, muscovite, biotite, garnet, quartz, albite, as well as locally chloritoid, amphibole, and rare kyanite. Plint & Jamieson (1989) estimated metamorphic temperatures to have been near 400–450°C in the low-grade belt on the basis of garnet–biotite geothermometry.

The Maritimes Basin (Howie & Barss 1975) unconformably covers much of the Canadian Appalachians in the vicinity of the Gulf of St. Lawrence. In the study area, volcanic rocks of the Fisset Brook Formation (Blanchard *et al.* 1984) constitute the basal member of the basin. The formation unconformably overlies the Cheticamp pluton or is in shear contact with the underlying JBMS. Late Devonian high-level granite intrusions are widespread throughout the Cape Breton Highlands, and the Salmon Pool Pluton (365 Ma; Barr 1990) is a large body of granite that has intruded the JBMS immediately adjacent to the mineralized area (Fig. 1).

THE SULFIDE LENSES

Nine sulfide occurrences, distributed along a 7-km north–south transect in the area near Faribault and Fisset brooks, were mapped during the course of this investigation (Fig. 1). The deposits are located near the sheared shallow-dipping contact between the lower mafic volcanic member and the upper clastic succession of the JBMS. A highly sheared rhyolite unit within the clastic succession hosts six of the occurrences; two others are contained within mafic volcanic rocks and one within quartz-pebble conglomerate. The rhyolite is between 2 m and 20 m thick, and is highly sericitized. Recrystallized quartz and sulfides form massive lenses from 5 to 30 cm thick, oriented parallel to schistosity and bedding. Lenses are typically lineated and boudinaged along north–south-trending axes. Disseminated and fracture-controlled sulfides surround the lenses; segmented boudinaged quartz veins up to 10 cm thick also are found. Arsenopyrite and pyrite in subequal proportions are the most abundant sulfides, forming up to 50–80% of the lenses, and are associated with variable proportions of sphalerite, galena and chalcopyrite, as well as minor bornite, pyrrhotite and tetrahedrite. Sphalerite or galena are only locally more abundant than arsenopyrite and pyrite. Samples rich in sphalerite are poor in chalcopyrite. Three of the sites visited, Galena Mine, Core Shack, and Fisset Brook (Fig. 1), contain samples with intergrowths of arsenopyrite – pyrite – pyrrhotite – sphalerite suitable for thermometric and barometric study. The other occurrences were lacking in either sphalerite or pyrrhotite.

Petrography

Sulfide lenses are thinly laminated, and invariably sheared. Laminations are mineralogically and

microstructurally inhomogeneous, resulting from varying degrees of recrystallization, cataclastic abrasion, and grain-size reduction induced during shear. Microstructures were studied in polished thin sections cut perpendicular to schistosity along the lineation.

The coarsest laminations consist of medium-grained equigranular quartz, and anhedral to subhedral pyrite and arsenopyrite. Quartz is generally strain-free and is recrystallized, with high-angle grain boundaries. Syn- and postkinematic growth of quartz and sulfide grains has resulted in layers from which kinematic information has been destroyed, and hence are strain-insensitive. However, polycrystalline monomineralic ribbons of quartz with oriented crystals are useful as indicators of shear sense. Remnant outlines of strained and recrystallized quartz-pebble clasts are observed in sandstone and conglomerate. The clasts are highly strained and flattened at a high angle to the bulk minimum axis of instantaneous stretching. Core and mantle textures (White 1976) within quartz clasts feature irregular serrated boundaries developed by grain-boundary migration and subgrain rotation.

Dynamic recrystallization of pyrite is demonstrated by coexisting coarse subhedral augen of pyrite and adjacent fine-grained monomineralic subaggregates. The subaggregates do not, however, preserve the original outlines of the pyrite crystals, but have been remobilized into sinuous forms bounded by shear bands. Rotation of pyrite augen is demonstrated by the development and preservation of displacement-controlled rigid fibers of quartz (Ramsay & Huber 1983) in the pressure fringes of pyrite cubes.

Sphalerite occurs as masses of anhedral grains interstitial to recrystallized subhedral crystals of pyrite and arsenopyrite. In some samples, sphalerite contains fine-grained inclusions or intergrowths of pyrrhotite, coexisting with coarser inclusions of arsenopyrite and pyrite (Figs. 2A,B).

MINERAL CHEMISTRY AND CONDITIONS OF FORMATION

Electron-microprobe analyses of arsenopyrite, sphalerite and pyrrhotite were done at the Geological Survey of Canada in Ottawa, using a Cameca SX–50 microprobe. Concentrations of the following eight elements were determined, with their detection limits noted in parts per million: Zn (840), Fe (375), Mn (525), Cd (1030), Co (475), Ni (640), S (1375), and As (560). An energy-dispersion spectrum indicated the absence of Cu within the sulfides. Analytical totals between 98.5 and 101.5 wt% were accepted. Results are presented as averages per locality in Table 1, and a complete data-set is available from the Depository of Unpublished Data, CISTI, National Research Council, Ottawa, Ontario K1A 0S2. Samples were taken from outcrops at locations shown in Figure 1.

Arsenopyrite

The arsenopyrite composition is relatively As-deficient, or S-rich. In the stoichiometric formula $FeAs_{1-x}S_{1+x}$, the value for x ranges between 0 and 0.13. Crystals are typically homogeneous, though one sample showed a marked As-enrichment toward the
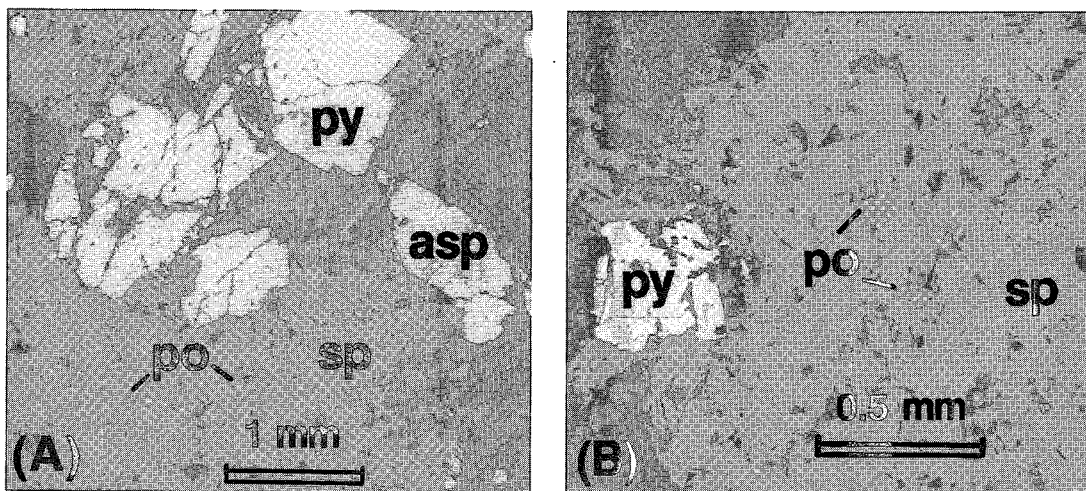

FIG. 2. Photomicrographs of polished sections from Galena Mine demonstrating close intergrowth of (A) subhedral arsenopyrite (asp) and pyrite (py), with massive sphalerite (sp) containing inclusions of pyrrhotite (po), and (B) fine-grained pyrite (py) – pyrrhotite (po) – sphalerite (sp) intergrowth.

TABLE 1. ARSENOPYRITE, PYRRHOTITE, AND SPHALERITE COMPOSITIONS (WT%)*

SAMPLE	Zn	Fe	Mn	Cd	Co	Ni	S	As	TOTAL
ARSENOPYRITE									
Galena Mine (6)	0.05	35.12	0.06	0.01	0.09	0.01	20.98	44.37	100.70
Core Shack (6)	0.01	35.79	0.03	0.03	0.05	0.01	21.74	43.24	100.90
Fisset Brook (9)	0.03	35.54	0.01	0.01	0.10	0.05	21.28	43.67	100.68
Campbell (4)	0.27	35.33	0.01	0.06	0.09	0.02	21.34	44.05	101.17
PYRRHOTITE									
Galena Mine (8)	0.77	59.48	0.07	0.04	0.06	0.02	39.26	0.14	99.83
Core Shack (7)	1.52	59.71	0.03	0.01	0.05	0.02	39.54	0.12	101.01
Fisset Brook (6)	0.06	60.25	0.00	0.03	0.05	0.02	39.64	0.13	100.18
SPHALERITE									
Galena Mine (8)	57.66	7.80	0.29	0.53	0.03	0.01	33.21	0.05	100.18
Core Shack (9)	58.52	7.65	0.36	0.42	0.01	0.02	33.22	0.04	99.57
Fisset Brook (6)	58.80	7.26	0.03	0.58	0.02	0.01	33.11	0.05	100.24
Campbell (4)	62.26	3.43	0.03	0.28	0.01	0.02	32.93	0.04	99.86

*Values are averages per locality for intergrown assemblages of sulfides, with number of analyses given in parentheses, outcrop samples from locations shown in Figure 1.

rim. The compositions are displayed in a triangular S–Fe–As diagram (Fig. 3), which includes compositional fields taken from the compilation of Sharp et al. (1985): arsenopyrite occurring with pyrite only, with pyrrhotite only, or with both pyrite and pyrrhotite. The samples analyzed span the field typical of arsenopyrite in equilibrium with pyrite and pyrrhotite, consistent with petrographic observations.

Although varying pressure may shift sulfidation buffer curves, it has only a minor effect on temperature determinations based on arsenopyrite coexisting with pyrite and pyrrhotite. Figure 4 is a temperature–composition diagram displaying the results from this study; temperature determinations show a wide range, from 300° to 510°C. Accordingly, the temperature variation is accompanied by a pronounced change in
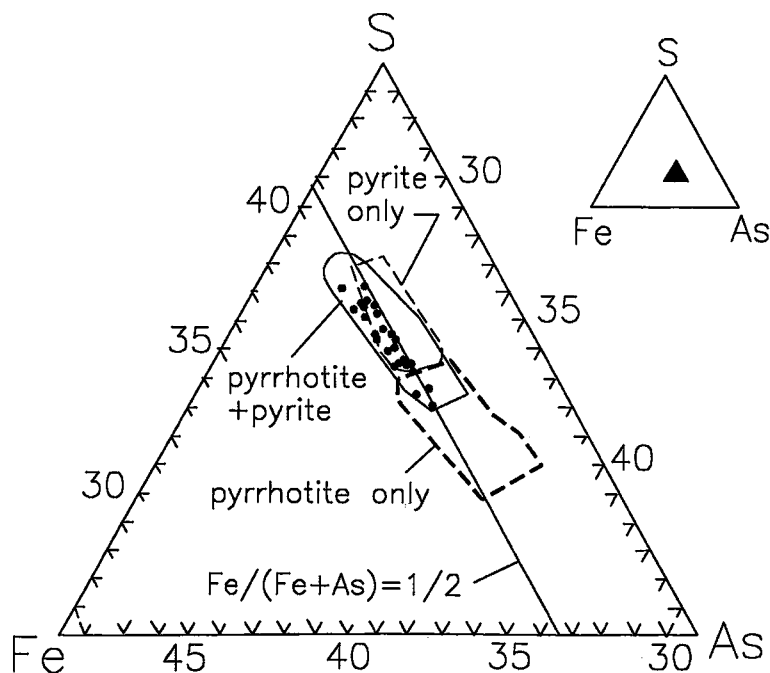

FIG. 3. S–Fe–As diagram showing compositional variation among analyzed grains of arsenopyrite. Also shown are general compositional fields for arsenopyrite coexisting with pyrite, with pyrrhotite, and with both pyrite and pyrrhotite (from compilation of Sharp et al. 1985).
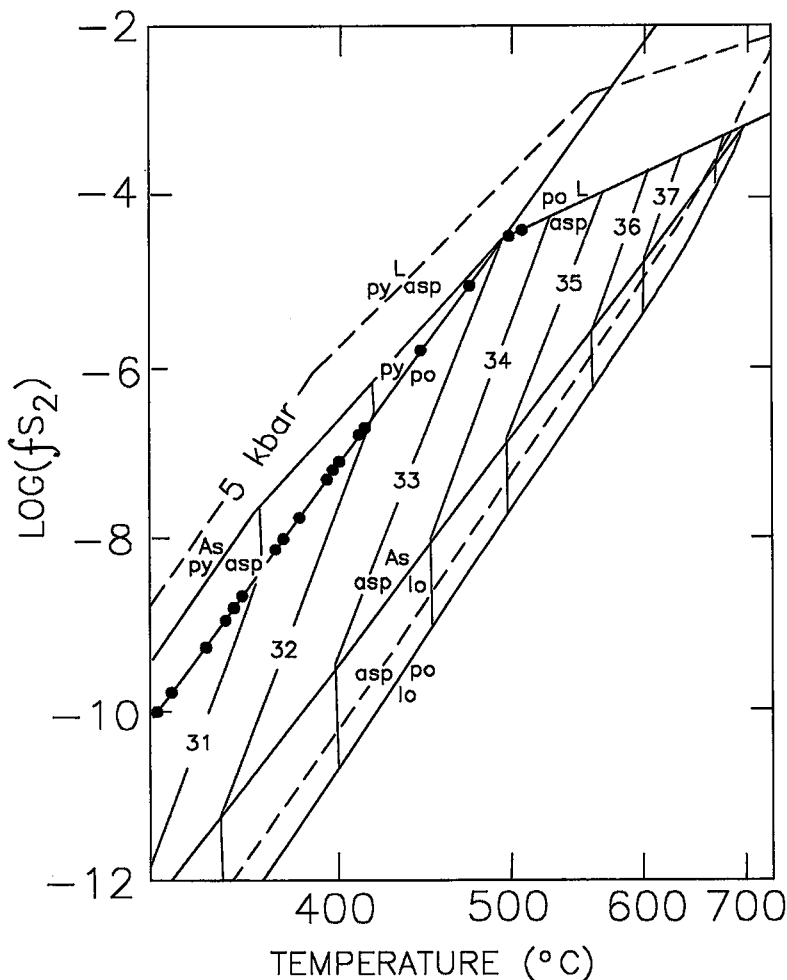
FIG. 4. Temperature determinations using the arsenopyrite geothermometer (Sharp *et al.* 1985), under conditions buffered by the pyrite–pyrrhotite solvus. A pressure change from 1 bar (solid lines) to 5 kilobars (dashed lines) has only a minor effect on the pyrite–pyrrhotite solvus, shifting the curve to a higher sulfidation state in a direction approximately parallel to the arsenopyrite isopleths; this influences temperature determinations only marginally. Abbreviations: asp arsenopyrite, lo löllingite, As arsenic, py pyrite, po pyrrhotite, L liquid. Numbers refer to arsenopyrite composition in atom % As; black dots represent arsenopyrite compositions from the present study plotted along the pyrite–pyrrhotite buffer.

the sulfur fugacity in the mineralizing environment because of the buffering capacity of coexisting pyrite and pyrrhotite (Fig. 4).

Pyrrhotite

Because of the closely intergrown nature of the sulfides and minute quantities of pyrrhotite, X-ray-diffraction analyses of sulfide mineral powders did not provide sufficient resolution to distinguish monoclinic from hexagonal pyrrhotite. However, the pyrrhotite's composition may give some insight into its structure (*e.g.*, Lusk *et al.* 1993). The atomic % Fe in pyrrhotite ranges from 45.9% to 47.3% (Fig. 5A). The composition is mostly Fe-deficient, with the formula $Fe_{1-x}S$, where x is between 0.15 and 0.10. The compositions cluster near Fe_7S_8 of the $4M$ polytype of (monoclinic) pyrrhotite (Nakazawa & Morimoto 1971) and reaches Fe_9S_{10} of $5H$ hexagonal pyrrhotite (polytype nomenclature according to Nickel 1993). However, the com-
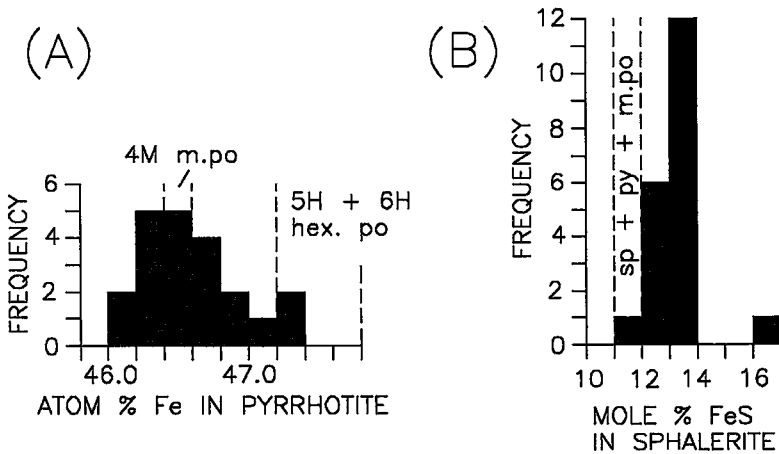
FIG. 5. A. Frequency plot of pyrrhotite compositions, with 4M monoclinic pyrrhotite field as well as field for 5H plus 6H hexagonal pyrrhotite displayed for reference (adapted from Nakazawa & Morimoto 1971, Lusk et al. 1993). B. Frequency plot of sphalerite compositions, with dashed lines outlining the field for sphalerite (sp) buffered by pyrite (py) and monoclinic pyrrhotite (m.po) between 11 and 12 mol % FeS.

position of many samples deviates from these ideal values. The absence of iron-rich pyrrhotite indicates that limited exsolution has occurred at low temperature (Nakazawa & Morimoto 1971). The range in values may be interpreted to indicate that hexagonal pyrrhotite was partly retrograded to monoclinic pyrrhotite at low temperatures, or it may have been affected by oxidation, producing sulfur enrichment (e.g., Lusk et al. 1993). Trace amounts of As were detected in the pyrrhotite, as well as significant quantities of Zn; however, the presence of Zn in the analytical data may reflect excitation of Zn in sphalerite due to the small size of the pyrrhotite inclusions.

Sphalerite

Compared with the known compositional range, the sphalerite grains analyzed in this study display a restricted composition. Only small or negligible amounts of Mn and Cd were detected in the samples, and Cu was not detected. The iron content is between 11 and 14 mol % FeS, with one value at 16.1%, and the greatest frequency lies between 13.0 and 13.5% (Fig. 5B). Such restricted iron content is typical of sphalerite occurring along the pyrite–pyrrhotite solvus, where the composition is approximately constrained to the interval 10–20 mol % FeS depending on pressure of formation (Scott & Barnes 1971, Scott 1973). An iron content of 13.0–13.5 mol % FeS in sphalerite is typical of sphalerite that has equilibrated with pyrite and hexagonal pyrrhotite (Lusk et al. 1993), with
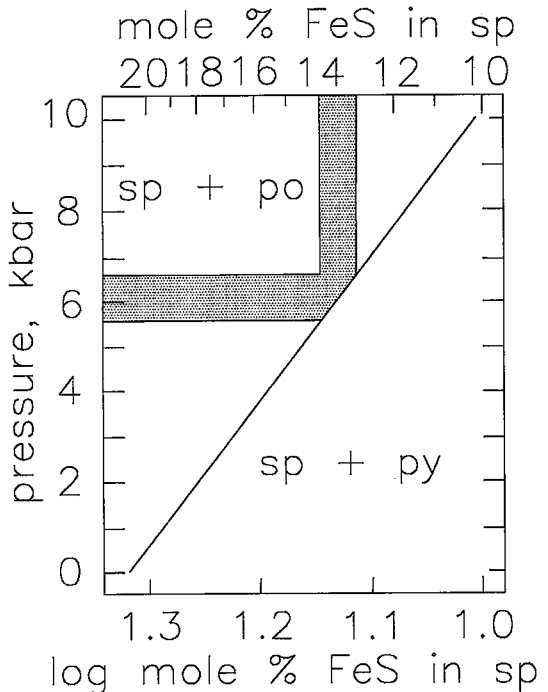

FIG. 6. Pressure determinations after method of Hutchison & Scott (1981) using highest frequency compositional range for sphalerite (see Fig. 5B).

TABLE 2.   P AND T DETERMINATIONS FROM INTERGROWTHS OF SPHALERITE-ARSENOPYRITE-
PYRRHOTITE-PYRITE

Sample	Mole % FeS sphalerite	Atom % As in arsenopyrite	T* (°C)	P** (kbar)	P*** (kbar)
Galena Mine 1	13.1	31.7	410	6.4	6.0
Galena Mine 2	13.4	32.3	450	6.1	6.2
Galena Mine 3	12.6	31.9	420	7.0	6.3
Galena Mine 4	13.9	33.6	510	5.6	6.4
Fisset Brook 1	13.2	33.1	490	6.3	6.9
Fisset Brook 2	12.9	32.8	480	6.6	6.9
Core Shack 2	13.2	31.2	380	6.3	5.5

*Arsenopyrite geothermometer, after Sharp et al. (1985).
**Sphalerite geobarometer after Hutchison and Scott (1985).
***Sphalerite geobarometer, after Toulmin et al. (1991).
Sample locations shown in Figure 1.

values distinctly higher than that which would be imposed by the pyrite – monoclinic pyrrhotite buffer (11–12 mol % FeS in sphalerite, Scott & Kissin 1973) (Fig. 5B). The range may be interpreted to indicate that sphalerite compositions reflect those established at high temperature.

Experimental calibration of the sphalerite geobarometer at high pressure (Scott 1973, Hutchison & Scott 1981) has established that the composition of sphalerite is sensitive to P but relatively insensitive to T. In the present study, estimates of P for closely intergrown sphalerite – pyrite – pyrrhotite – arseno-

pyrite range from 5.6 to 7.0 kilobars, based on the geobarometer of Hutchison & Scott (1981) (Fig. 6, Table 2), and a compositional range of 13 to 14 mol % FeS in sphalerite. However, the thermodynamic calculations of Toulmin et al. (1991) suggest that pressure determinations are more strongly influenced by temperature, which for this study produce estimates of 5.5 to 6.9 kilobars if combined with temperature determinations based on arsenopyrite (Fig. 7, Table 2). Although application of the two methods leads to some discrepancy, similar results are attained.
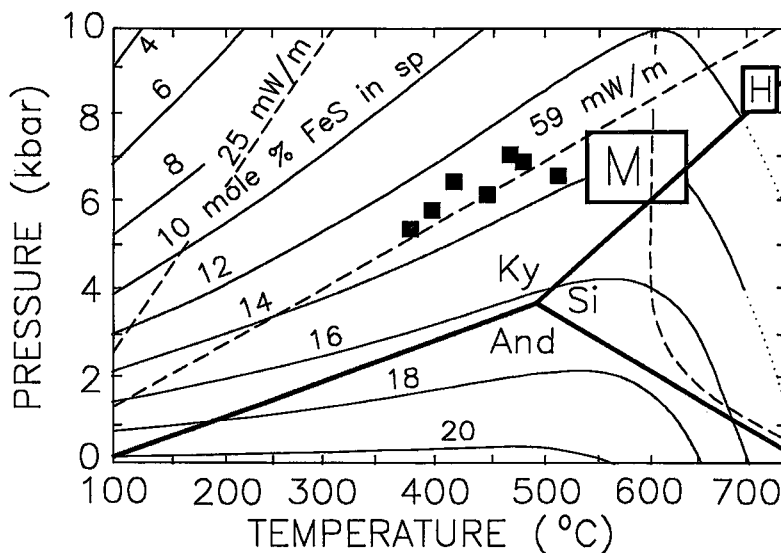

FIG. 7. Pressure estimates (black squares) made from sphalerite – pyrrhotite – pyrite – arsenopyrite intergrowths using arsenopyrite geothermometer (Fig. 4) and pressure–temperature diagram for sphalerite of Toulmin et al. (1991). Boxes marked M and H refer to the pressure and temperature conditions determined by Plint & Jamieson (1989) for the medium- and high-grade zones adjacent to the mineralized area (Fig. 1). Dashed lines represent known geothermal gradients; the partly vertical dashed line is the water-saturated granodiorite solidus (Toulmin et al. 1991).

DISCUSSION

Sulfide mineral equilibria assist in characterizing the low-grade metamorphic belt. Metamorphic conditions established with the sulfide assemblages are consistent with the metamorphic zonation determined from silicate assemblages, demonstrating the usefulness of the sulfides in the study of metamorphism. Cyclical growth of grains (Chatterjee 1980), precipitation, and recrystallization have preserved phases formed under different physical–chemical conditions, and document a dynamically evolving system. In particular, the range in composition of arsenopyrite produced while buffered along the pyrite–pyrrhotite solvus provides clear evidence of retrograde conditions during metamorphism. In contrast, sphalerite has a more uniform composition, possibly because sphalerite isopleths follow certain geothermal gradients in P–T space (Fig. 7) (Toulmin et al. 1991). In the low-grade belt, Plint & Jamieson (1989) bracketed the temperature of metamorphism using the garnet–biotite geothermometer at about 400°–450°C, which agrees well with the higher determinations of temperature based on arsenopyrite (Fig. 4). Pressure estimates from sphalerite, placed at between 6 and 7 kilobars, provide useful information on the relative motion of thrust blocks; the adjacent high-grade belt (Fig. 1) was metamorphosed to 8–10 kilobars (Plint & Jamieson 1989) and subsequently thrust over the low-grade belt (Craw 1984, Lynch & Tremblay 1992), transported upward by the vertical equivalent of some 1 to 4 kilobars.

The presently stratiform and stratabound nature of the sulfide lenses, their polymetallic character, as well as their association with an Ordovician–Silurian volcanic-sedimentary sequence and close spatial association to a specific rhyolite unit, have led several investigators to postulate a primary exhalative origin for the sulfides in relation to volcanism within the JBMS (Currie 1987, Sangster et al. 1990, Jamieson et al. 1990, Mengel et al. 1991). These authors recognized the recrystallized, remobilized, and partly discordant aspects of the sulfides. On the other hand, Chatterjee (1980) concluded from petrographic observations that the mineralization represents polycyclic hydrothermal deposits that postdate their host rocks. Hence, both syngenetic and epigenetic interpretations have been proposed for the origin of the occurrences. Typically, arsenopyrite is a secondary accessory mineral in volcanogenic massive sulfide deposits (e.g., Large 1992); however, deposits that contain significant quantities are known (e.g., Sundblad et al. 1984, Trepka-Bloch 1989). Furthermore, a genetic relationship with volcanism may be inferred by the spatial association of the occurrences with a rhyolite unit occurring along the contact between volcanic and sedimentary cycles.

CONCLUSIONS

Microstructures of host rocks and sulfide lenses, as well as the spatial distribution of sulfides, are interpreted to be products of crystallization during shear and metamorphism. Despite these masking effects, a primary exhalative origin for the metal concentrations is likely.

Coexisting sphalerite, arsenopyrite, pyrrhotite and pyrite provide constraints on the conditions of temperature, pressure, and sulfidation. The assemblage allows documentation of both peak and retrograde phenomena under greenschist-facies conditions, which typically are difficult to characterize. Metamorphic conditions are estimated to have ranged from about 510°C and 6.9 kilobars at peak conditions, down to less than 300°C and 4.0 kilobars during retrogression.

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