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FACTORS CONTROLLING THE OCCURRENCE OF FERRO-AXINITE WITHIN ARCHEAN GOLD-COPPER-RICH QUARTZ VEINS: COOKE MINE, CHIBOUGAMAU AREA, ABITIBI GREENSTONE BELT*

BENOÎT DUBÉ** AND JAYANTA GUHA

*Sciences de la Terre, Centre d'Étude sur les Ressources Minérales, Université du Québec à Chicoutimi,
Chicoutimi, Québec G7H 2B1*

ABSTRACT

Boron is commonly associated with gold mineralization, as suggested by the widespread occurrence of tourmaline in gold-bearing quartz veins. Axinite, a calc-silicate of boron, is rarer than tourmaline and generally is not observed in association with auriferous zones. This paper documents occurrences of ferro-axinite associated with gold-copper-rich quartz veins at the Cooke mine, near Chibougamau, in the Abitibi greenstone belt. At the Cooke mine, pinkish violet ferro-axinite commonly occurs in auriferous quartz veins, in barren calcite-quartz extension-related veins, in hydrothermal breccias, and within or near late brittle faults. Cross-cutting relationships and strain compatibility indicate that the late brittle faults and the gold-hosting structures were formed in a relatively short period of time. The FeO content of the axinite is high (8%), whereas MgO is low (2%). Composition variations are limited and do not seem to correlate with distinct environments of formation, despite the different modes of occurrence. The formation of ferro-axinite is considered to occur where carbonatization is limited, so that the available Ca combines with B, Fe, and Si from the hydrothermal fluid to form ferro-axinite rather than tourmaline. This reaction occurred early, as the ferro-axinite is commonly attached to the walls of the veins, whereas the sulfides surround and partly replace the ferro-axinite. The similarity in composition of the ferro-axinite associated with mineralized veins and with late brittle faults suggests that both structures were infiltrated by the boron-rich fluid. The formation of ferro-axinite rather than tourmaline is also strongly promoted by a Ca- and iron-rich environment. The study illustrates the strong influence of the composition of the host rock and of the hydrothermal fluid on the formation of ferro-axinite.

Keywords: ferro-axinite, gold, copper, boron, K-feldspar, Bourbeau sill, Cooke mine, Chibougamau, Abitibi Greenstone Belt, Quebec.

SOMMAIRE

Le bore est communément associé aux minéralisations aurifères, comme le suggère la présence fréquente de tourmaline dans les veines de quartz aurifère. L'axinite, un calco-silicate de bore, est plus rare que la tourmaline et n'est généralement pas associée aux zones aurifères. Nous documentons la présence de la ferro-axinite associée à des veines de quartz riches en or et en cuivre à la mine Cooke, près de Chibougamau, dans la ceinture de roches vertes de l'Abitibi. À la mine Cooke, l'axinite rose violacé est répandue dans les veines de quartz aurifère, dans des veines d'extension stériles composées de calcite-quartz, dans des brèches hydrothermales, et dans des failles cassantes tardives, ou à proximité de ces dernières. Les relations de recoupement et de compatibilité de la déformation indiquent que les failles tardives cassantes et les structures hôtes de la minéralisation aurifère se sont formées durant une période relativement courte. Le contenu en FeO de l'axinite est élevé (environ 8%), alors que celui en MgO est faible (<2%). Les variations en composition de la ferro-axinite sont limitées et ne semblent pas pouvoir être associées à des milieux de formation spécifiques malgré les différents types de mise en place. La formation de la ferro-axinite serait liée à un milieu où la carbonatation est faible; ainsi, le Ca disponible se combine avec le B, Fe, et Si provenant du fluide pour former la ferro-axinite plutôt que la tourmaline. Cette réaction se produit précocement, étant donné que la ferro-axinite est généralement attachée aux murs des veines, alors que les sulfures entourent et remplacent partiellement la ferro-axinite. La présence de ferro-axinite de composition similaire associée aux veines minéralisées et aux failles cassantes tardives indique que les deux structures ont été infiltrées par le fluide riche en bore. La formation de ferro-axinite plutôt que de tourmaline est également fortement influencée par l'abondance de Ca et de fer disponibles dans le milieu de formation. Cette étude illustre l'influence de la composition de la roche-hôte et du fluide hydrothermal sur la formation de la ferro-axinite.

Mots-clés: ferro-axinite, or, cuivre, bore, feldspath potassique, sill de Bourbeau, mine de Cooke, Chibougamau, ceinture de roches vertes de l'Abitibi, Québec.

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** Present address: Commission géologique du Canada, Centre géoscientifique de Québec, 2700, rue Einstein, C.P. 7500, Sainte-Foy, Québec G1V 4C7.

INTRODUCTION

The association of boron with gold mineralization is relatively common, as suggested by the occurrence of tourmaline in gold-bearing quartz veins (Boyle 1979, Roberts 1987). Axinite, a boron-bearing calcisilicate, is rarer than tourmaline, and its occurrence in association with auriferous mineralization is much less common. On the other hand, axinite is relatively common in manganese and ferruginous ore deposits, contact metamorphic and metasomatic ore deposits, granitic pegmatites and associated high-temperature environments, regionally metamorphosed rocks, and veins in igneous and sedimentary rocks (Simonen & Wiik 1952, Deer *et al.* 1962, Mozgova 1964, Carstens 1965, Serdyuchenko & Makarov 1971, Ozaki 1970, 1972, Lumpkin & Ribbe 1979, Pringle & Kawachi 1980, Sonnet & Verkaeren 1989). Its association with fracture fillings along or near fault zones has been documented by Hietanen & Erd (1978). Its relationship with gold mineralization has been reported by Boyle (1979) and, in the Timmins area, where axinite and clinozoisite occur chiefly in veins located on the fringe of quartz-ankerite gold-bearing veins, by Hurst (1935). Suzuki & Fujiwara (1971) have reported on gold mineralization in axinite-quartz veins emplaced

within bodies of diabase. They contended that the gold-bearing axinite-quartz veins are produced by a hydrothermal solution related with an orogenic movement and not with a skarn or igneous activity. Jébrak *et al.* (1991) reported the presence of Mg-rich axinite as a metamorphic phase in early carbonatized andesites in the McWatters gold mine on the Cadillac break, in Abitibi, Quebec. They noted the early replacement of axinite by tourmaline and suggested that boron was first incorporated in axinite and only later precipitated to form gold-associated tourmaline.

Axinite is a common mineral in Archean rocks of the Chibougamau – Chapais mining district, where it is reported from both mineralized and barren areas (Buchan 1964, 1976, Dubé & Guha 1989, Dubé 1990). In this study, we document the occurrence of ferro-axinite associated with gold-copper-rich veins and determine why axinite is found at Chibougamau rather than the more common tourmaline associated with the majority of Archean mesothermal gold deposits.

REGIONAL SETTING

The Chibougamau – Chapais mining district is located about 600 km north of Montreal, at the eastern end of the Chibougamau–Matagami Greenstone Belt

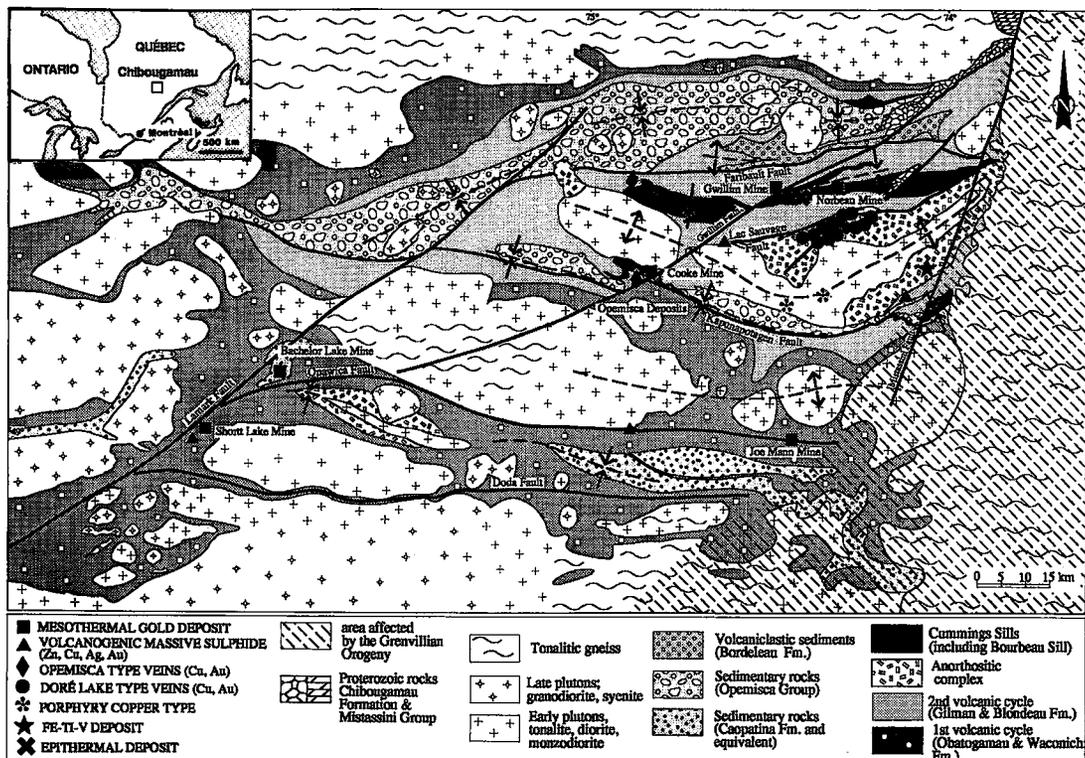


FIG. 1. Regional geological map of the Chibougamau area (modified from Guha *et al.* 1990a).

of the Superior Province, where the Abitibi Subprovince is truncated by the Grenville Front (Fig. 1). The Chibougamau – Chapais area consists of a sequence of volcanic (Roy Group) and volcano-sedimentary rocks (Opemisca Group) of Archean age. Detailed descriptions are given by Allard *et al.* (1985).

The Bourbeau sill, which hosts the gold mineralization at the Cooke mine, is at the top of the mafic-ultramafic Cummings Complex of three sills emplaced in lavas and felsic volcanogenic sediments of the Blondeau Formation. Regionally, the Bourbeau sill is a layered iron-rich gabbro of tholeiitic affinity (Duquette 1976, Dubé & Guha 1989). The sill differentiated into units that comprise, upward from the base, peridotite–pyroxenite, leucogabbro, quartz ferrogabbro, quartz ferrodiorite, and local upper ferro-gabbro (Dubé & Guha 1989).

Dimroth *et al.* (1986) and Daigneault *et al.* (1990) summarized the four successive regional structural events of importance: (1) synvolcanic structures, (2) large east–west regional folds and reverse ductile faults formed during the Kenoran orogeny, (3) north-east-trending sinistral faults of probable Late Archean age, reactivated during the Early Proterozoic, and (4) NNE-trending Grenvillian faults (Fig. 1).

GEOLOGY OF THE COOKE MINE

The Cooke mine is a Au–Cu–Ag deposit hosted in Archean rocks of the Superior Province. The mine produced more than 2 million tonnes of ore at a grade of 5.04 g/t Au, 0.66% Cu and 10 g/t Ag. The mine is located 5 km northeast of the two major Opemisca copper–gold deposits (Springer and Perry mines; Fig. 2), which have had a combined production of more than 24 million tonnes of ore grading of 2.40% Cu and less than 1 g/t Au.

Stratigraphic and structural relations of the study area are based on the work of Lavoie (1972), on maps of the underground workings, and on recent detailed mapping by Dubé & Guha (1989) and Dubé (1990). The local stratigraphic section comprises volcanoclastic felsic rocks of the Blondeau Formation intruded by the Bourbeau sill (Fig. 2). The Bourbeau sill, which hosts the gold–copper mineralization, is, at the Cooke mine, a 400-m-thick layered mafic intrusion containing at least three different units: 1) a basal pyroxenite, 2) a leucogabbro, and 3) an upper quartz ferrogabbro.

In the Cooke mine area, the main faults are the Gwillim Lake Fault (Dimroth *et al.* 1984, Dubé & Guha 1992), which is a regional NE–SW brittle–ductile oblique fault more than 100 km long with an oblique sinistral displacement of several km, the NNE Chibougamau – Copper Fault, characterized by a sinistral oblique-reverse movement (Dubé & Guha 1992), and the E–W Kapunapotagen Fault. The Gwillim Lake fault cuts the latter ones. The Cooke mine is located between the Gwillim Lake Fault and

the Chibougamau–Copper Fault (Fig. 2).

The gold–copper mineralization is found in sulfide-rich quartz, calcite, ferro-axinite or K-feldspar veins from a few cm to few m wide. These veins are located within two main brittle to brittle–ductile shear zones or fractures oriented NW–SE to E–W and known as the no. 7 and 9 veins. Overall, these structures are sub-parallel to stratigraphic contacts and are interpreted to be syntectonic (Dubé & Guha 1992). At depth (> 400 m), however, the structures are discordant. The auriferous structures have lateral and vertical extensions of more than 500 m. The gold–copper veins are confined to the Bourbeau sill and are generally sub-parallel to the shear zones. The mineralized shear zones were produced by a subhorizontal, north–south-directed shortening compatible with the Kenoran orogeny (Dubé & Guha 1992). The shears are offset by oblique northeast-trending sinistral and local north–south dextral brittle faults. These faults, as well as the regional Gwillim Lake and Chibougamau – Copper faults, are products of the same subhorizontal, north–south-directed shortening and regional strain-regime. However, cross-cutting relationships and strain compatibility indicate that the Gwillim Lake fault formed slightly later than the gold-hosting shear zones in an event of progressive deformation (Dubé & Guha 1992).

The sulfide content of the mineralized veins varies from traces to 90 vol. %. The sulfides are mainly chalcopyrite, with a lesser proportion of pyrrhotite, arsenopyrite and pyrite. Most grains of gold are present as inclusions or as fracture fillings within the sulfides. Thin veinlets of orange to red K-feldspar containing fine hematite dusting are commonly observed at the vein – wallrock contact, in the mineralized or barren deformed zones, and less commonly in veinlets that cut weakly deformed gabbro. “Hematization” of K-feldspar is a common process (Rosenqvist 1951, Boone 1969), and its relationship with gold mineralization has been discussed by various investigators (Boyle 1979, Cameron & Hattori 1987).

The hydrothermal alteration of wallrocks is relatively weak, and characterized by chloritization of the pyroxene, amphibole and plagioclase adjacent to the veins and sericitization of the plagioclase farther away (Dubé 1990). These hydrothermal minerals replace the regional metamorphic assemblages, indicating that mineralization postdates the peak of the greenschist-facies regional metamorphism.

OCCURRENCES OF FERRO-AXINITE AT THE COOKE MINE

Pinkish violet axinite was first reported in the mineralized samples of the Cooke mine by Buchan (1976). In fact, axinite is observed in different environments. It is present in sulfide-rich auriferous quartz

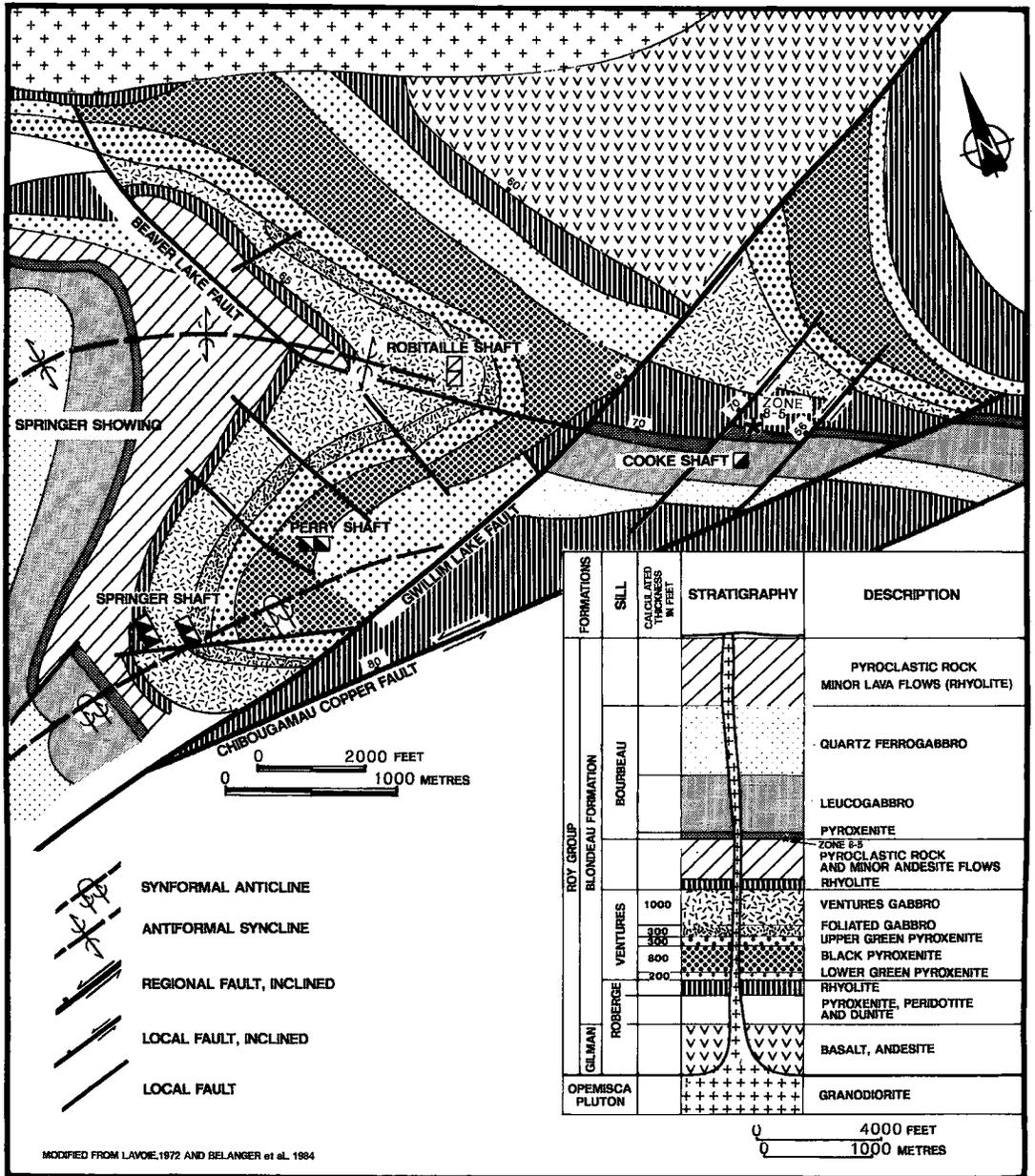


FIG. 2. Geological setting of the Cooke mine, modified from Lavoie (1972) and Bélanger *et al.* (1984).

veins (Fig. 3A), and in calcite-quartz extension veins away from the mineralized shear-zones (Fig. 3B), in hydrothermal breccia developed in unstrained or weakly deformed gabbroic rocks (Fig. 3C), and inside fault gouge or veinlets located near the faults. These veinlets are either oriented subparallel or oblique to the faults (Fig. 3D). Ferro-axinite identification is confirmed by powder X-ray diffractometry.

The mineralized zones

Quartz and calcite, commonly with ferro-axinite and K-feldspar, are the chief gangue minerals in the auriferous veins (Figs. 3A-B). Typically, the veins are zoned, with the outer parts composed of quartz and ferro-axinite and K-feldspar; the central parts are composed of quartz, calcite and sulfides, commonly with

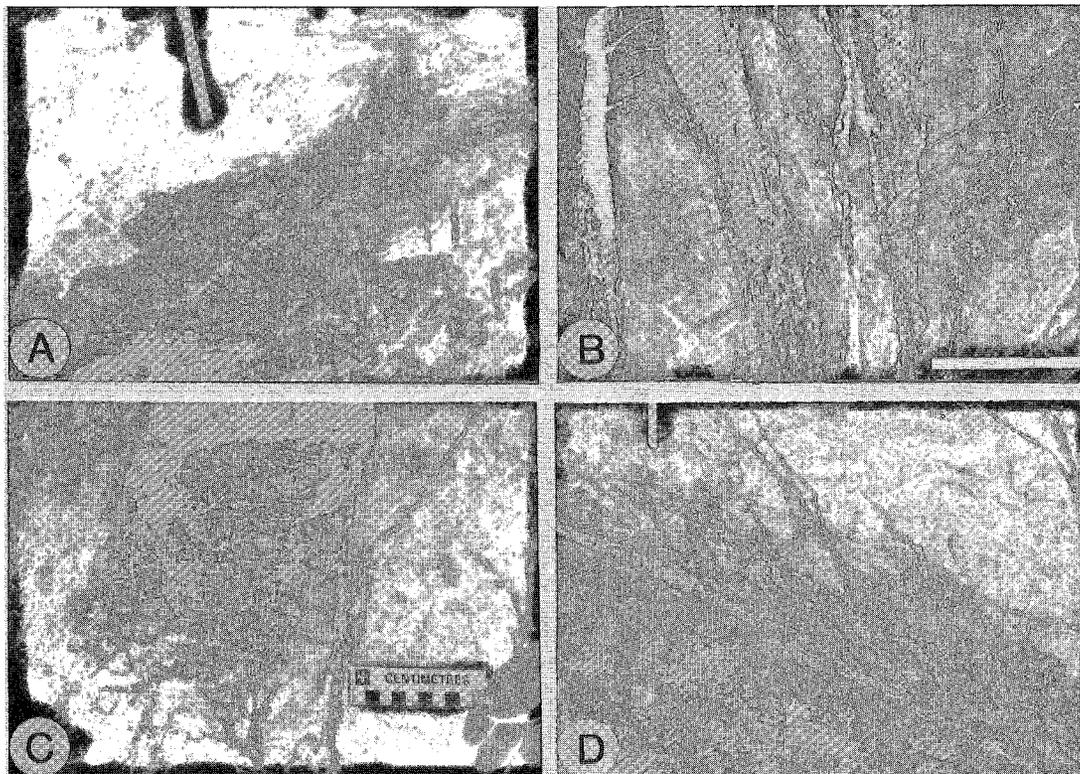


FIG. 3. A. Ferro-axinite-rich mineralized vein (scale bar equals 16 cm). B. Extensional ferro-axinite veins (scale bar equals 25 cm). C. Example of hydrothermal ferro-axinite-rich breccia. D. Ferro-axinite veinlets spatially associated with a late brittle fault (scale bar equals 6 cm).

K-feldspar and ferro-axinite (Figs. 4A–B). In general, these minerals are deformed. Quartz is polygonized (Fig. 4C); the pyrite and arsenopyrite have been submitted to cataclastic deformation, whereas the chalcopyrite and pyrrhotite were affected by ductile deformation, recrystallized and were probably remobilized in openings and fractures in the other brittle sulfides.

Ferro-axinite forms crystals 0.5 mm to 1 cm attached to the walls of the veins. It is one of the first hydrothermal minerals to have precipitated. Ferro-axinite commonly forms euhedral crystals oriented subperpendicular to the walls, suggesting that it crystallized as open-space fillings in the absence of any stress (Fig. 4A). Ferro-axinite constitutes up to 30% of some veins. Chalcopyrite is common as inclusions or is enclosed in ferro-axinite as fracture fillings. In places, the ferro-axinite is totally surrounded by chalcopyrite. Elsewhere, it is partly replaced by chalcopyrite and pyrrhotite (Fig. 4D). As with the other vein minerals, the ferro-axinite has been deformed (Fig. 5A). It shows undulatory extinction and locally

contains fractures filled by calcite, or it is surrounded by recrystallized quartz. Locally, ferro-axinite occurs as subrounded fragments in a matrix of chalcopyrite or pyrrhotite and is replaced by secondary amphibole, calcite or quartz. Locally, K-feldspar attached to the vein walls is surrounded by ferro-axinite or is partly replaced by ferro-axinite (Figs. 4A–B), thereby suggesting that at least some of the ferro-axinite precipitated later than the K-feldspar during the same mineralizing event.

Hydrothermal breccia and barren extension-related veins

In hydrothermal breccia and barren extension-related veins, ferro-axinite is observed as 2 mm to 1 cm crystals associated with quartz, calcite and traces of tourmaline and amphibole. In general, ferro-axinite, quartz and feldspar are attached to the walls of the veins, whereas calcite is in the interior. In the breccia, the ferro-axinite is observed as fracture fillings and as replacements of the gabbroic host-rocks. Preserved

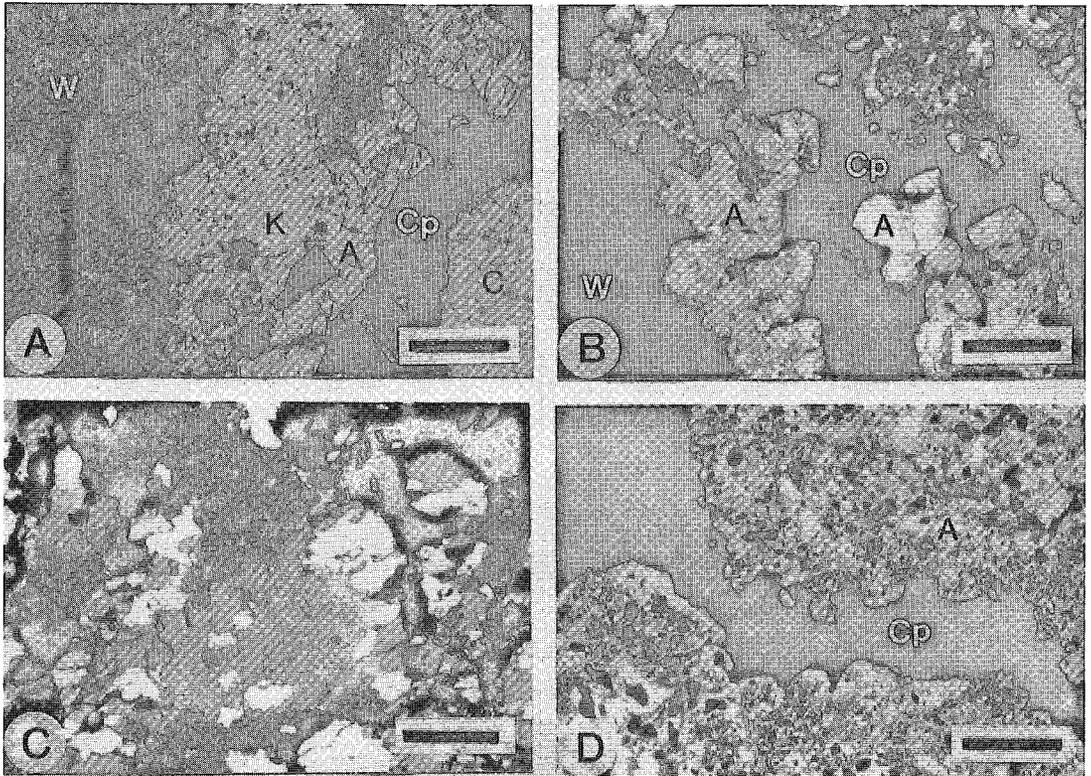


FIG. 4. Photomicrographs showing A. typical assemblage at the vein – wallrock (W) contact composed of feldspar (K), ferro-axinite (A), chalcopyrite (Cp) and calcite (C); B. euhedral crystals of ferro-axinite (A) subperpendicular to the walls of a chalcopyrite-rich (Cp) vein and suggesting open-space filling; C. polygonized quartz; D. ferro-axinite (A) partly replaced by chalcopyrite (Cp). Scale bar equals 0.35 cm except in C, where it is 1 cm.

grains of primary titaniferous magnetite replaced by leucoxene and totally surrounded by ferro-axinite suggest that the ferro-axinite was formed by replacement of feldspar, pyroxene and amphibole of the gabbroic host-rocks (Fig. 5C). The ferro-axinite is usually slightly deformed and cut by calcite veinlets. Locally, it is partly replaced by calcite, chlorite and epidote. Tourmaline grains are locally observed and are partly replaced by ferro-axinite.

The fault zones

Ferro-axinite is present as a strongly deformed mineral in the gouge of late brittle faults (Figs. 3D, 5D). It is present within polymineralic porphyroclasts (0.05–0.2 mm) of feldspar, hornblende, quartz and tourmaline, or as small fragments in a matrix of euhedral tourmaline and actinolite. The ferro-axinite shows undulose extinction and polygonization, and has fractures commonly filled by calcite. One ferro-

axinite phenoclast was observed to contain traces of chalcopyrite, suggesting that ferro-axinite and chalcopyrite are contemporaneous and that both minerals were strongly deformed by late faulting. Thus it is assumed that the ferro-axinite and chalcopyrite are early relative to late faulting, although repeated movements along the fault also may be responsible for deformation of minerals contemporaneous with the fault.

Textural relationships show that the ferro-axinite is related to the same hydrothermal event leading to the precipitation of the sulfides and the gold mineralization. Ferro-axinite does not present textural evidence that suggests a late filling or replacement in the mineralized zones following their re-opening associated with late movement along faults. The occurrence of ferro-axinite in veinlets subparallel or discordant to the brittle faults is puzzling. Was this fault-related ferro-axinite produced by remobilization from previous gold-related ferro-axinite?

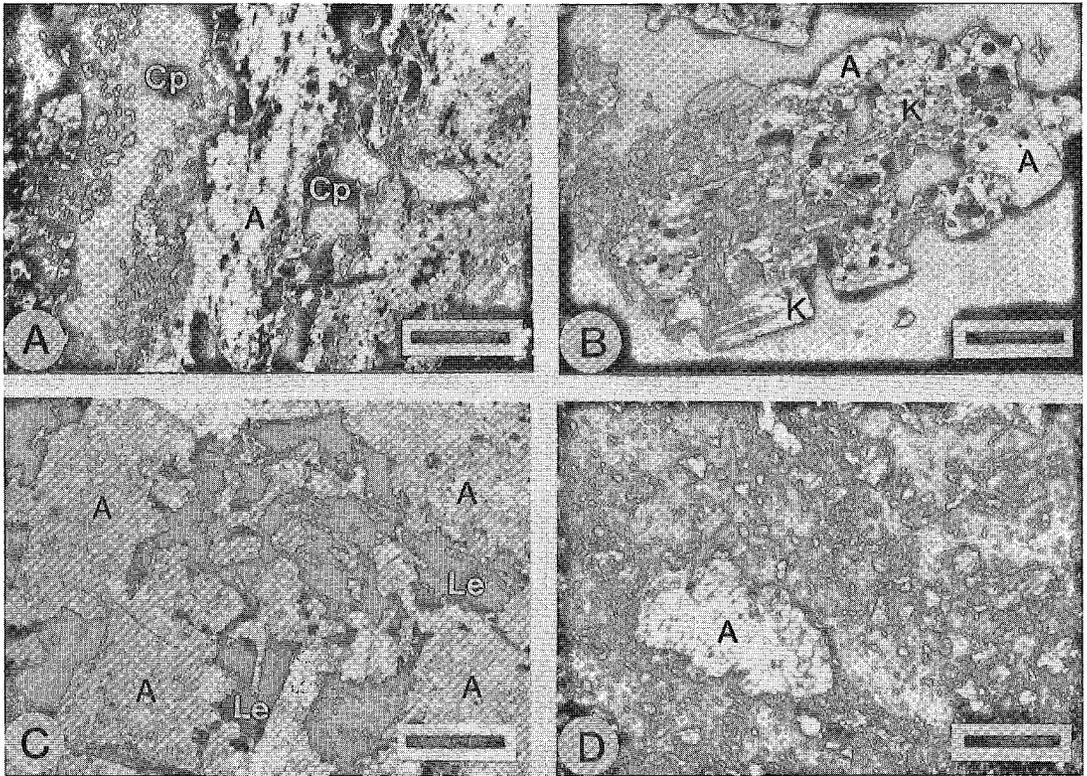


FIG. 5. Photomicrographs showing A. deformed ferro-axinite (A) and associated chalcocopyrite (Cp); B. K-feldspar (K) partly replaced by ferro-axinite (A); C. titaniferous magnetite replaced by leucoxene (Le) and totally surrounded by ferro-axinite (A), and D. ferro-axinite (A) phenoclast within cataclasite. Scale bar equals 0.35 cm.

CHEMICAL COMPOSITION OF FERRO-AXINITE

Forty-six spot analyses were carried out on seven representative samples from three different occurrences, namely, extension-related barren veins, mineralized veins and the late brittle faults (Table 1). Analyses were obtained using a Material Analysis Company electron microprobe equipped with a Kevex 7000 energy-dispersion spectrometer standardized against natural and synthetic minerals. Analytical conditions (accelerating voltage 20 kV, beam current 10 nA) and data reduction were controlled and processed through a Digital PDP1103-L computer using the Geological Survey of Canada software EDDI. The relative accuracy of the analyses varies from 1–2% of the amount present for major element, to 10% for trace elements. Results were corrected for background, overlap and matrix effects (ZAF) (Love & Scott 1981, Myklebust *et al.* 1979).

As done by Pringle & Kawachi (1980), cationic

proportions were calculated on an anhydrous and boron-free basis (Table 1). Concentrations of water and B_2O_3 have not been determined, and are allocated in stoichiometric proportions: $OH = 2.0$ and $B = 2.0$. Total iron is expressed as Fe^{2+} , the amount of Fe^{3+} in the formula has been calculated on the basis of $(IVAl + Ti + Fe^{3+}) = 4.000$. As suggested by Pringle & Kawachi (1980), the tendency for the analytical total to approach 100% (Table 1) supports the accuracy of this modified calculation.

Results of the microprobe analyses closely approach both the general formula for the axinite group, $A_3Al_2BSi_4O_{15}$, where $A = Ca, Fe^{2+}, Mg, Mn^{2+}$ (Fleischer & Mandarino 1991), as well as the ideal formula of axinite proposed by Lumpkin & Ribbe (1979): $(Mn, Fe^{2+}, Mg, Zn, Al_w)(Ca_{2-x}Mn_x) VI(Al_{2-y}Fe^{3+}_y)_2(OH_{2-w}O_w) IV[B_2Si_{8-z}Al_z]O_{30}$, where $w < 1, x < 1, y \ll 1, z \ll 1$. The high FeO content, with Fe greater than Mn, and the cationic proportion of Ca greater than 1.5, show that the mineral is ferro-axinite

TABLE 1. AVERAGE COMPOSITION* OF FERRO-AXINITE AT THE COOKE MINE

Sample number	PB-113-86B	PB-118-86	PB-641-85B	PB-105-85	PB-100-85	PB-642-85	PB-249-86	PB-145-85	**
Number of analyses	9	4	2	6	4	4	4	10	
Occurrence	Gold veins			Barren veins			Fault		
SiO ₂ (%)	42.51	43.31	43.46	42.51	43.31	43.46	42.94	42.73	SiO ₂ (%) 42.47
TiO ₂	0.01	0.04	0.05	0.01	0.04	0.05	0.04	0.03	TiO ₂ 0.19
Al ₂ O ₃	17.04	17.29	17.39	17.04	17.29	17.39	16.97	16.99	Al ₂ O ₃ 18.47
FeO	7.76	8.45	7.72	7.76	8.45	7.72	8.59	8.13	FeO 6.57
MnO	2.12	2.34	2.09	2.12	2.34	2.09	1.72	1.30	MnO 1.46
MgO	1.67	1.33	1.81	1.67	1.33	1.81	1.48	2.10	MgO 2.08
CaO	20.33	20.54	20.70	20.33	20.54	20.70	20.34	20.35	CaO 19.93
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	Na ₂ O 0.00
K ₂ O	0.05	0.06	0.07	0.05	0.06	0.07	0.04	0.11	K ₂ O 0.21
Total	91.49	93.36	93.29	91.49	93.36	93.29	92.17	91.74	Fe ₂ O ₃ 1.19
									H ₂ O* 0.07
H ₂ O*	1.59	1.60	1.61	1.58	1.61	1.56	1.59	1.58	H ₂ O* 1.61
B ₂ O ₃ *	6.11	6.20	6.23	6.10	6.21	6.04	6.14	6.13	B ₂ O ₃ 5.87
									Total 100.12
Formula (basis of 32 O, OH)									
Si	8.056	8.067	8.065	8.056	8.067	8.065	8.088	8.060	Si 7.939
									Al 0.061
Ti	0.001	0.005	0.007	0.001	0.005	0.007	0.006	0.004	Ti 0.054
Al	3.806	3.796	3.804	3.806	3.796	3.804	3.766	3.777	Al 4.013
Fe ^{3+***}	0.193	0.199	0.189	0.193	0.199	0.189	0.228	0.219	Fe ³⁺ 0.167
	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.234
Fe ²⁺	1.036	1.117	1.008	1.036	1.117	1.008	1.125	1.064	Fe ²⁺ 1.028
Mn	0.340	0.369	0.328	0.340	0.369	0.328	0.275	0.207	Mn 0.231
Mg	0.473	0.370	0.501	0.473	0.370	0.501	0.415	0.589	Mg 0.580
Ca	4.128	4.100	4.115	4.128	4.100	4.115	4.104	4.113	Ca 3.995
K	0.012	0.013	0.017	0.012	0.013	0.017	0.010	0.027	K 0.049
	5.989	5.969	5.969	5.989	5.969	5.969	5.929	6.000	5.883
OH*	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	OH 2.009
B*	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	B 1.895
Molar %									
Mn	5.97	6.38	5.82	5.97	6.38	5.82	4.80	3.70	
Ca	72.46	70.87	72.96	72.46	70.87	72.96	71.60	73.41	22.89
Fe	21.57	22.75	21.22	21.57	22.75	21.22	23.60	22.89	22.89

* The atomic proportions have been calculated, as proposed by Pringle & Kawachi (1980), on an anhydrous and boron-free basis. Water and B₂O₃ contents are estimated in stoichiometric amounts: OH = 2.0, and B = 2.0.

** Example of axinite composition, taken from Deer *et al.* (1962).

*** Calculated; see text.

(Sanero & Gottardi 1968). The chemical compositions of the ferro-axinite from the three distinct settings within the deposit show little variation on the classification diagram proposed by Ozaki (1972) (Fig. 6). All compositions are located in an area overlapping the fields that characterize axinite from veins enclosed in igneous and sedimentary rocks, from regional metamorphic rocks, and from contact metamorphic and metasomatic ore deposits.

FLUID-INCLUSION DATA

A reconnaissance study of fluid inclusions was

principally undertaken to examine the CO₂ and H₂O content of the fluid associated with the formation of the ferro-axinite. Most of the inclusions are primary in nature, distributed mainly as single isolated inclusions within grains of ferro-axinite. The very small dimension of the inclusions (≤ 10 μm) makes a detailed study impossible. However, the few inclusions (11) that could be studied indicate that they are essentially aqueous, with no visible CO₂. Homogenization temperatures range between 180 and 280°C. Only two melting temperatures of ice could be determined (-27.5°C and -51°C), indicating the presence of divalent cations such as Ca and Mg (Crawford 1981).

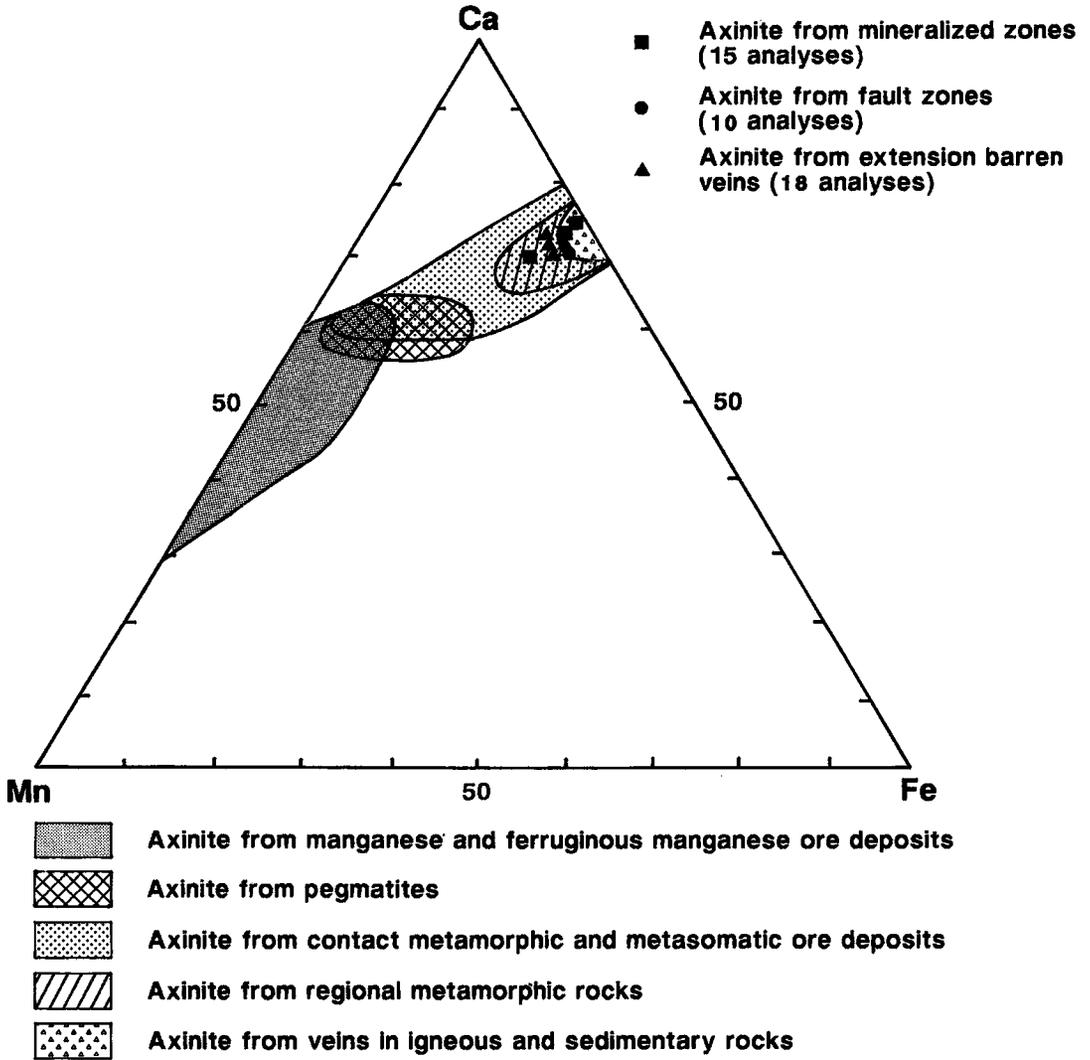


FIG. 6. Triangular diagram showing axinite compositions according to Ozaki (1972), and the distribution of the ferro-axinite compositions according to their distinct settings at the Cooke mine.

Since clathrates could not be observed owing to the small dimension of the inclusions, a more sophisticated technique, solid probe mass spectrometry (SPMS) had to be used to ascertain the level of CO₂ in the inclusions. The SPMS technique, which has been described in detail in Guha *et al.* (1990b, 1991), allows us to identify with a greater degree of accuracy the minor components of the fluid. Table 2 shows that fluid inclusions related to the formation of the ferro-axinite associated with the mineralization are essentially free of CO₂. Although only a small number of inclusions has been studied, the microthermometric results and SPMS investigations emphasize that a

H₂O-rich fluid is associated with the formation of ferro-axinite.

TABLE 2. COMPOSITION OF TRAPPED FLUID RELATED TO THE FORMATION OF FERRO-AXINITE

Sample number	CH ₄	H ₂ O	CO ₂
PB-113-86B	3.0	92.8	0.2
PB-841-85B	5.2	84.8	1.6
PB-842-85	9.3	81.6	1.0

DISCUSSION AND CONCLUSIONS

Ferro-axinite at the Cooke mine formed from hydrothermal fluids circulating in the shear zones. Most likely, boron was derived from a hydrothermal fluid circulating through shear zones and fractures, and leaching volcanic and sedimentary rocks. The mass-balance lithogeochemical study of the altered wallrock indicates that Ca was leached, whereas Fe was added (Dubé 1990). The Ca liberated would normally combine with CO₂ present in the hydrothermal fluid to form carbonates so typical of Archean mesothermal gold deposits (Roberts 1987). The fluid-inclusion data indicate the paucity of CO₂ during the formation of the ferro-axinite. The extent of carbonatization is relatively limited in the Cooke mine, indicating that all the liberated Ca has not been fixed by the CO₂. Thus, a significant amount of Ca was available to combine with the B present in the hydrothermal fluid to form axinite. As previously mentioned, gangue tourmaline is usually observed in gold-bearing veins or wallrock; tourmaline, however, does not contain significant Ca (<2–3% CaO), whereas Ca is one of the principal constituents of axinite (up to 20% CaO). The B, Fe and Si present in the fluid phase have combined with Ca, allowing the formation of ferro-axinite. This reaction seems to be one of the first ones to occur. That ferro-axinite is paragenetically younger than the sulfides and gold is evident from its occurrence along the wall of the veins and its partial replacement by the surrounding sulfides. Similar textural relationships have been reported by Mozgova (1964) and Serdyuchenko & Makarov (1971). The textural relationships suggest that the ferro-axinite is in essence contemporaneous with gold mineralization.

Structural interpretation of the mineralized veins and the late brittle faults suggests that the two structures were formed in a relatively short period of time (Dubé & Guha 1992). As the brittle faults are later than the auriferous mineralization, the ferro-axinite in the fault zones may be mainly related to deformation of the previously deposited ferro-axinite contemporaneous to the event of gold mineralization. It cannot be precluded, however, that the fault-related ferro-axinite is partly related to a second generation of formation. The presence of ferro-axinite of similar composition associated both with the mineralized veins and the late fault-zone may indicate that both structures were infiltrated by the boron-rich fluid; as the structures are interpreted to have formed in a relatively short period of time, the same conditions controlling the formation of ferro-axinite may have prevailed.

At the Sigma mine, Val d'Or, Quebec, Al and Ca, initially present in the wallrock, were mobilized under the influence of the hydrothermal fluid (Robert & Brown 1986). These elements were incorporated into the fluid and were precipitated as tourmaline and carbonate minerals in the veins. At the Cooke mine, a

mass-balance lithogeochemical study demonstrates that Al was relatively immobile in comparison to the other major elements, and Ca was leached and incorporated into the hydrothermal fluid to form ferro-axinite (Dubé 1990). These results are compatible with data published by Hurst (1935), Vallance (1966), and Mansergh & Watters (1969), who suggested that the formation of ferro-axinite rather than tourmaline results from a Ca-rich environment. Hietanen & Erd (1978) suggested that the high iron content of ferro-axinite is a reflection of a high iron content of the host rock in which the axinite-bearing veins occur (up to 10.30% FeO and 3.62% Fe₂O₃ at the Cooke mine). In a general perspective, this study illustrates the strong influence of the composition of the host rock and of the hydrothermal fluid, and their resultant interaction, on the formation of ferro-axinite in Archean gold deposits.

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REFERENCES

- ALLARD, G.O., CATY, J.-L. & GOBEL, A. (1985): The Archean supracrustal rocks of the Chibougamau area. *In* Evolution of Archean Supracrustal Sequences (L.D. Ayres, P.C. Thurston, K.D. Card & W. Weber, eds.). *Geol. Assoc. Can., Spec. Pap.* **28**, 55-63.

- BÉLANGER, J., GUHA, J., COULOMBE, A. & CARIGNAN, J. (1984): The 8-5 zone, Cooke mine, Chapais: a volcanogenic massive sulphide deposit in the Blondeau Formation. In *Chibougamau - Stratigraphy and Mineralization* (J. Guha & E.H. Chown, eds.). *Can. Inst. Min. Metall., Spec. Vol. 34*, 271-287.
- BOONE, G.M. (1969): Origin of clouded red feldspars: petrologic contrasts in a granitic porphyry intrusion. *Am. J. Sci.* **267**, 633-668.
- BOYLE, R.W. (1979): The geochemistry of gold and its deposits. *Geol. Surv. Can., Bull.* **280**.
- BUCHAN, R. (1964): Report on investigations of samples submitted by Opemiska Copper Mines Ltd. Internal report for the company (unpubl.).
- (1976): Mineralogical examination of gold-bearing samples from Cooke mine, Opemiska. *Falconbridge Nickel Mines Ltée, Metallurgical Lab. Rep. Ministère de l'Énergie et des Ressources du Québec*, **G.M. 36317**.
- CAMERON, E.M. & HATTORI, K. (1987): Archean gold mineralization and oxidized hydrothermal fluids. *Econ. Geol.* **82**, 1177-1191.
- CARSTENS, H. (1965): Contributions to the mineralogy of Norway. 32. Axinite in the Norwegian Caledonides. *Norsk Geol. Tidsskr.* **45**, 397-415.
- CRAWFORD, M.L. (1981): Phase equilibria in aqueous fluid inclusions. In *Fluid Inclusions: Applications to Petrology* (L.S. Hollister & M.L. Crawford, eds.). *Mineral. Assoc. Can., Short-Course Handbook 6*, 75-100.
- DAIGNEAULT, R., ST-JULIEN, P. & ALLARD, G.O. (1990): Tectonic evolution of the northeast portion of the Archean Abitibi Greenstone Belt, Chibougamau area, Quebec. *Can. J. Earth Sci.* **27**, 1714-1736.
- DEER, W.A., HOWIE, R.A. & ZUSSMAN, J. (1962): *Rock-Forming Minerals. 1. Ortho- and Ring Silicates*. Longman, Green and Co., London.
- DIMROTH, E., ARCHAMBAULT, G., GOULET, N., GUHA, J. & MUELLER, W. (1984): A mechanical analysis of the late Archean Gwillim Lake shear belt, Chibougamau area, Quebec. *Can. J. Earth Sci.* **21**, 963-968.
- , MUELLER, W., DAIGNEAULT, R., BRISSON, H., POITRAS, A. & ROCHELEAU, M. (1986): Diapirism during regional compression: the structural pattern in the Chibougamau region of the Archean Abitibi belt, Québec. *Geol. Rundschau* **75**, 715-736.
- DUBÉ, B. (1990): *Métallogénie aurifère du filon-couche de Bourbeau, région de Chibougamau*. Thèse de doctorat, Université du Québec à Chicoutimi, Chicoutimi, Québec.
- & GUHA, J. (1989): Étude métallogénique (aurifère) du filon-couche de Bourbeau, région de Chibougamau: synthèse finale. *Ministère de l'Énergie et des Ressources du Québec MM 87É03*.
- & —— (1992): Relationship between NE trending regional faults and Archean mesothermal gold-copper mineralization: Cooke mine, Abitibi greenstone belt, Quebec, Canada. *Econ. Geol.* **87**, 1525-1540.
- DUQUETTE, G. (1976): North half of McKenzie and Roy townships and northwest quarter of McCorkill township. *Ministère des Richesses Naturelles, Québec DPÉ357*.
- FLEISCHER, M. & MANDARINO, J.A. (1991): *Glossary of Mineral Species 1991*. The Mineralogical Record Inc., Tucson, Arizona.
- GUHA, J., CHOWN, E.H., ARCHAMBAULT, G., BARNES, S.-J., BRISSON, H., DAIGNEAULT, R., DION, C., DUBÉ, B., MUELLER, W. & PILOTE, P. (1990a): Metallogeny in relation to magmatic and structural evolution of an Archean greenstone belt: Chibougamau mining district. In *Gold and Base-Metal Mineralization in the Abitibi Subprovince, Canada, with Emphasis on the Quebec Segment* (compiled by S.E. Ho, F. Robert & D.I. Groves). *Department of Geology and University Extension, University of Western Australia, Publ.* **24**, 121-166.
- , LU, HUANG-ZHANG, DUBÉ, B., ROBERT, F. & GAGNON, M. (1991): Fluid characteristics of vein and altered wall-rock in Archean mesothermal gold deposits. *Econ. Geol.* **86**, 637-684.
- , —— & GAGNON, M. (1990b): Gas compositions of fluid inclusions using solid probe mass spectrometry and its application to study of mineralizing processes. *Geochim. Cosmochim. Acta* **54**, 553-558.
- HIETANEN, A. & ERD, R.C. (1978): Ferroaxinites from the Feather River area, northern California and from the McGrath and Russian Mission quadrangles, Alaska. *J. Res. U.S. Geol. Surv.* **6**, 603-610.
- HURST, M.E. (1935): Vein formation at Porcupine, Ontario. *Econ. Geol.* **30**, 103-127.
- JÉBRAK, M., MINEAU, R., BARDOUX, M. & GOULET, N. (1991): Boron cycle in the Abitibi greenstone belt, and compositional variations in tourmaline associated with gold deposits. In *Greenstone Gold and Crustal Evolution. Proc. Nuna Conf. (Val d'Or, Québec)* (F. Robert, P.A. Sheahan & S.B. Green, eds.). *Geol. Assoc. Can., Mineral Deposits Div.*, (abstr.).
- LAVOIE, J. S. (1972): Geology of Opemiska mines. Internal report, Falconbridge Copper Limited, Opemiska Division (unpubl.).
- LOVE, G. & SCOTT, V.D. (1981): Updating correction procedures in quantitative electron-probe microanalysis. *Scanning* **4**, 111-130.
- LUMPKIN, G.R. & RIBBE, P.H. (1979): Chemistry and physical properties of axinites. *Am. Mineral.* **64**, 635-645.
- MANSERGH, G.D. & WATTERS, W.A. (1969): A note on axinite from Aviemore, Waitaki Valley. *N.Z. J. Geol. Geophys.* **13**, 725-727.

- MOZGOVA, N.N. (1964): Axinite and datolite from polymetal skarn deposits in the Far East. *Int. Geol. Rev.* **6**, 682-689.
- MYKLEBUST, R.L., FIORI, C.E. & HEINRICH, K.F.J. (1979): FRAME C: a compact procedure for quantitative energy-dispersive electron probe X-ray analysis. *Nat. Bur. Standards, Tech. Note* **1106**.
- OZAKI, M. (1970): The chemical variation of axinite in reference to their modes of occurrence. *J. Jap. Assoc. Mineral. Petrol. Econ. Geol.* **64**, 157-172.
- (1972): Chemical composition and occurrence of axinite. *Kumamoto J. Sci., Geol.* **9**, 1-34.
- PRINGLE, I.J. & KAWACHI, Y. (1980): Axinite mineral group in low-grade regionally metamorphosed rocks in southern New Zealand. *Am. Mineral.* **65**, 1119-1129.
- ROBERT, F. & BROWN, A.C. (1986): Archean gold-bearing quartz veins at the Sigma mine, Abitibi greenstone belt, Quebec. II. Vein paragenesis and hydrothermal alteration. *Econ. Geol.* **81**, 593-616.
- ROBERTS, R.G. (1987): Ore deposits models. 11. Archean lode gold deposits. *Geosci. Can.* **14**, 37-52.
- ROSENQVIST, I.T. (1951): Investigations in the crystal chemistry of silicates. III. The relation haematite-microcline. *Norsk Geol. Tidsskr.* **29**, 65-76.
- SANERO, E. & GOTTARDI, G. (1968): Nomenclature and crystal chemistry of axinites. *Am. Mineral.* **53**, 1407-1411.
- SERDYUCHENKO, D.P. & MAKAROV, V.N. (1971): New data on magnesium-iron axinite from Pechenga and on the chemical composition in general. *Dokl. Acad. Sci. USSR, Earth Sci. Sec.* **197**, 128-130.
- SIMONEN, A. & WIIK, H.B. (1952): The axinites from Jokioinen and Petsamo. *Bull. Soc. Géol. Finlande* **157**, 1-6.
- SONNET, P.M. & VERKAEREN, J. (1989): Scheelite-, malayaite-, and axinite-bearing skarns from El Hammam, central Morocco. *Econ. Geol.* **84**, 575-590.
- SUZUKI, M. & FUJIWARA, T. (1971): Gold-bearing axinite-quartz veins in the diabase zone along the western margin of the Hidaka belt, Hokkaido. *J. Jap. Assoc. Mineral., Petrol., Econ. Geol.* **65**, 39-48.
- VALLANCE, T.G. (1966): A contact metamorphic axinite paragenesis at London Bridge, near Queanbeyan, N.S.W. *R. Soc. New South Wales J. Proc.* **99**, 57-67.

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