The Crescent Lake copper deposit, central Newfoundland: deep levels of a volcanogenic hydrothermal system?

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The Crescent Lake Mine, near the village of Robert's Arm in central Newfoundland, produced small tonnages of high-grade copper ore from quartz veins in the late 1800's and the 1920's. Although a Crescent Lake-type deposit is not a viable exploration target in itself, its presence has been used to suggest a potential for either volcanogenic massive sulphides (VMS) such as the nearby Pilley's Island deposit, or for mesothermal or epithermal gold. Field relationships, petrography, geochemistry, mineral chemistry, and fluid inclusion and stable isotopic studies are used to constrain the genesis of the deposit. Mineralization occurs in four sulphide stages and a late oxide stage, distinguished by ore microscopy. Sphalerite, galena, chalcopyrite, and newly recognized carrollite were deposited with quartz between two pyrite stages. Covellite and iron oxides indicate later oxidation. Fluid inclusions in vein quartz are aqueous fluid-vapour type with no daughter crystals, no CO_2 or CH_4, no boiling, and a narrow range of salinities (~ 3-7% $NaCl_{equiv}$). The sulphides were likely deposited from homogeneous fluids at >430 m depth. The wide range of homogenization temperatures (~112-250°C) can be interpreted as the result of either changing temperature or fluctuating fluid pressures during the episodic crack-seal vein formation. Ore-related chlorite has a distinctive blue birefringence and higher Fe/Fe+Mg values (~ 0.51 vs. 0.42) than chlorite in barren host rock, similar to other VMS deposits. The average calculated crystallization temperature of hydrothermal chlorite (240 ± 2°C) is close to the maximum fluid inclusion homogenization temperatures and likely closer to the true fluid trapping temperature. Sulphur isotope determinations ($\partial^{34}S_{py} \approx 5.4$; $\partial^{34}S_{cp} \approx 2.8$; $\partial^{34}S_{sp} \approx 2.2$) are similar to the Gull Pond VMS deposit; they indicate isotopic disequilibrium between coeval sulphides but a homogeneous sulphur source during the ore-forming event. This study concludes that the Crescent Lake copper deposit is most likely part of a volcanogenic hydrothermal stockwork, possibly genetically related to the Pilley's Island deposit.

La mine de Crescent Lake, située dans la région centrale de Terre-Neuve à proximité du village de Robert's Arm, produisit de faibles tonnages de minerai à forte teneur en cuivre, issu de veines de quartz, vers la fin des années 1800 et dans les années 1920. Bien qu'un gîte de type Crescent Lake tout seul ne constitue pas une cible d'exploration viable, sa présence a été utilisée pour suggérer l'éventualité soit d'amas sulfurés volcanogènes(ASV), tel que le gîte avoisinant de Pilley's Island, soit d'or méso- ou épithermal. La confrontation des données concernant les rapports sur le terrain, la pétrographie, la géochimie, la chimie des minéraux, ainsi que l'étude des inclusions fluides et des isotopes stables, est employée pour définir la genèse du gîte. La minéralisation se présente sous forme de quatre stades à sulfures et d'un stade tardif à oxydes, que l'on reconnaît à l'aide de la microscopie métallographique. La sphalérite, la galène, la chalcopyrite ainsi qu'une carrollite découverte récemment, se sont accumulées avec du quartz entre deux stades à pyrite. De la covellite et des oxydes de fer témoignent d'une oxydation ultérieure. Les inclusions fluides au sein du quartz filonien sont du type à fluide aqueux et vapeur, sans crystaux rejetons, CO_2, CH_4 ni ébullition, et montrent une gamme peu étendue de salinités (~ 3-7% équiv. NaCl). Il semble que les sulfures aient précipité à partir de fluides homogènes à une profondeur dépassant 430 m. Les valeurs très dispersées des températures d'homogénéisation (~112-250°C) pourraient résulter soit de changements de température, soit de fluctuations dans la pression du fluide, durant la formation épisodique de filons par colmatage de fractures en traction. La chlorite alliée au minerai possède une biréfringence bleue caractéristique et des valeurs plus élevées du rapport Fe/Fe+Mg (~ 0.51 vs. 0.42) que la chlorite présente dans la roche encaissante stérile, ce qui s'apparente aux autres gisements ASV. La moyenne calculée des températures de cristallisation de la chlorite hydrothermale (240 ± 2°C) se situe près des températures maximales d'homogénéisation des inclusions fluides et s'approche vraisemblablement plus des températures réelles de capture des fluides. Le dosage des isotopes du soufre ($\delta^{34}S_{py} \approx 5.4$; $\delta^{34}S_{cp} \approx 2.8$; $\delta^{34}S_{sp} \approx 2.2$) ressemble à celui du gisement ASV de Gull Pond; il témoigne d'un déséquilibre isotopique entre des sulfures synchrones mais aussi d'une source homogène du soufre durant l'épisode métallogène. Une conclusion de cette étude est que

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le gîte cuprifère de Crescent Lake fait le plus vraisemblablement partie d'un stockwerk volcanogène hydrothermal, possiblement relié par sa genèse au gîte de Pilley's Island.

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INTRODUCTION

The Crescent Lake Mine, located near the village of Robert's Arm in the Green Bay, Notre Dame Bay area of central Newfoundland (Fig. 1), is the largest of a number of epigenetic base metal prospects associated with quartz veining and wall-rock alteration in the Robert's Arm-Crescent Lake area. In the late 1800's, 1100 tonnes of chalcopyrite ore grading 28% Cu were mined from this small, rich, quartz vein-hosted copper deposit (Espenshade, 1937). Subsequently, from 1924 to 1926, 1800 tonnes of 12% Cu ore were removed. The property has been explored since 1926 by various companies but with discouraging results (MacQuarrie, 1976).

Three inclined shafts follow the dip of the main vein toward Crescent Lake and two vertical shafts intersect the easternmost inclined shaft (Espenshade, 1937). At present the shafts are filled with rubble, and most of the dump material was removed for road and wharf construction in 1974 (Swinden *et al.*, 1988).

Two genetic models have been proposed for the deposit on the basis of field characteristics. Wallrock alteration and sulphide mineralization is similar to that of the nearby Pilley's Island volcanogenic massive sulphide deposit (Fig. 1), suggesting an analogy with a deep-level stockwork formed in a volcanogenic hydrothermal system (Swinden *et al.*, 1988). Alternatively, the sheeted quartz veining suggests a syn-tectonic mesothermal or epithermal vein deposit formed when metals indigenous to the volcanics were tectonically remobilized during later faulting (Bostock, 1978).

Although a Crescent Lake-type deposit is not a viable exploration target in itself, its genesis has direct implications for the exploration industry. On one hand, the deposit may indicate the presence of volcanogenic massive sulphides higher in the stratigraphy; on the other, it may represent the effects of the mesothermal gold event which is now widely recognized in central Newfoundland (Tuach *et al.*, 1988).

This paper presents field relationships, petrography, geochem-

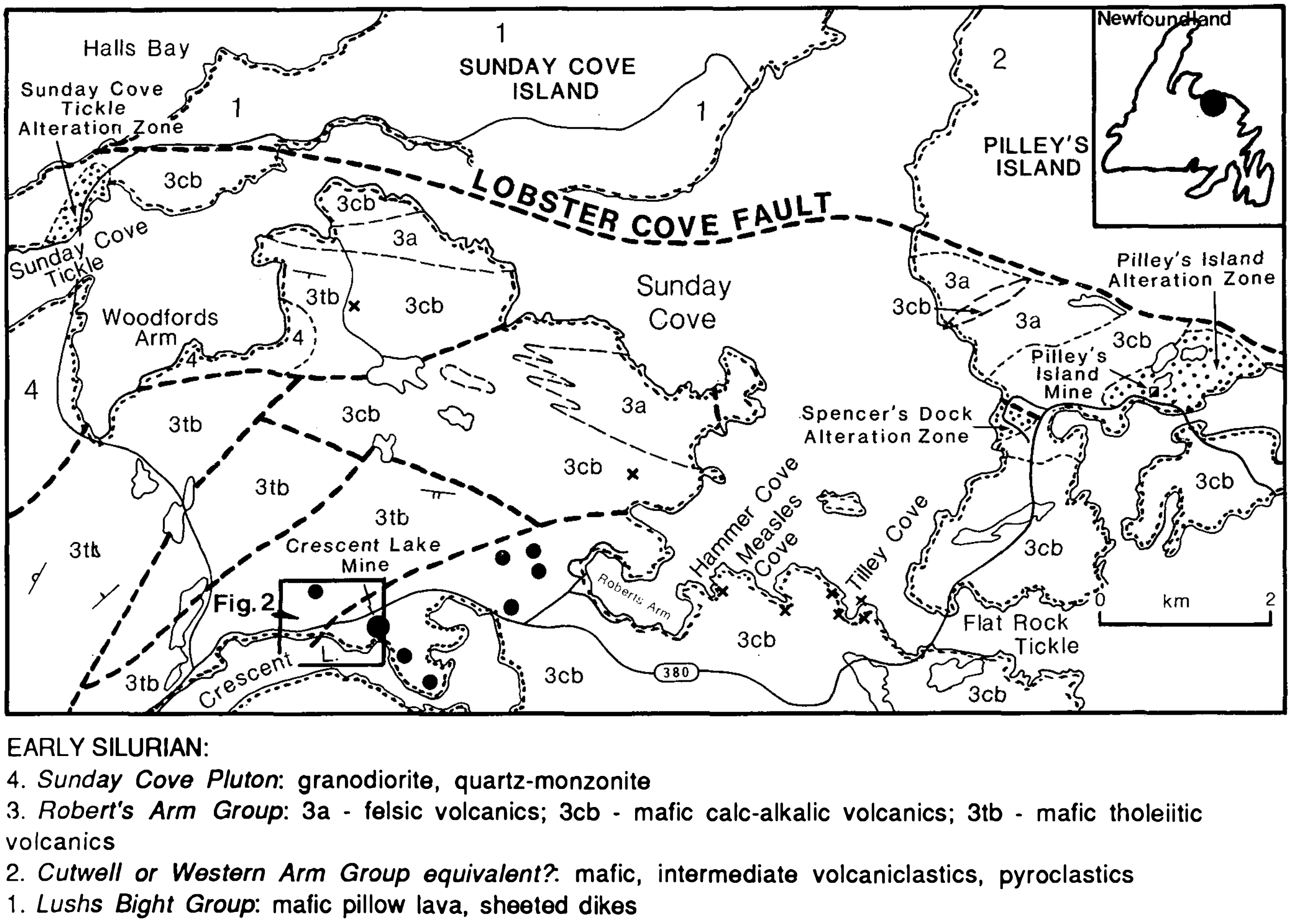

Fig. 1. Location (shown on inset map of Newfoundland) and generalized geology (after Bostock, 1978) of the Crescent Lake and Pilley's Island area. Alteration zones in stipple are after Tuach (1984). Mineral occurrences of Crescent Lake-type shown by solid dots; faults shown by heavy dashed lines (after Swinden, 1987).

istry, mineral chemistry, fluid inclusion studies, and stable isotopic studies carried out to constrain the genesis of the deposit, and provides evidence that it might well represent the deep levels of a volcanogenic hydrothermal system.

GEOLOGIC SETTING

Regional geology

The Crescent Lake Mine is hosted by Lower Ordovician volcanic rocks of the Robert's Arm Group (Fig. 1). Regionally, this group forms part of an extensive belt of dominantly calc-alkalic, mafic, and lesser felsic volcanic rocks termed the "Buchans-Robert's Arm Belt" (Strong, 1977; Dean, 1978). This volcanic belt is generally considered to be an island arc in the Ordovician "Iapetus" ocean (Strong, 1977; Thurlow *et al.*, 1975; Bostock, 1988). The Buchans-Robert's Arm belt is a prolific host of volcanogenic massive sulphide deposits, with major former producers at Buchans, Gullbridge, and Pilley's Island, and scores of lesser prospects and showings (Kean *et al.*, 1981; Swinden and Sacks, 1986; Bostock, 1988).

The Crescent Lake Mine is the largest of several small base metal prospects associated with quartz veining and wall rock alteration in the area between Robert's Arm and Crescent Lake (Fig. 1). The Robert's Arm Group in the area comprises a dominantly north-facing sequence of mafic pillow lavas, which has been disrupted by a number of prominent strike-slip faults (Bostock, 1988) (Fig. 2). The deposit occurs just north of a terrane-bounding major fault ("Crescent Lake-Sops Arm Fault" of Bostock, 1988), near the structural and stratigraphic base of a thick (>3 km) sequence of basalts interpreted as calc-alkalic on the basis of major element geochemistry (Bostock, 1988).

The volcanism north of Crescent Lake becomes more silicic up-section, and the exposed top of the succession, in the Sunday Cove and Pilley's Island areas, is characterized by considerable volumes of dacite and rhyolite (Fig. 1). On Pilley's Island, a dacite dome interbedded with calc-alkalic pillow basalts hosts, and is genetically related to the Pilley's Island volcanogenic massive sulphide deposit (Tuach, 1984). Similar volcanic alteration occurs at approximately the same stratigraphic horizon on Sunday Cove Island (Sunday Cove Tickle alteration zone; Fig. 1). Stratigraphic reconstruction indicates that the Pilley's Island deposit may be as much as 2000 m stratigraphically above the Crescent Lake Mine, although movement along the intervening faults is poorly constrained.

Geochemistry of Robert's Arm volcanics

In an effort to confirm the calc-alkalic nature of the volcanic pile and to test whether volcanic rocks in the Crescent Lake area can be considered part of a continuous volcanic sequence, including the volcanogenic massive sulphides at Pilley's Island, several samples from Bostock (1988) from the two areas were analyzed for additional trace elements including rare earth elements (REE) (Fig. 3a, b). Major elements and the trace elements Cr, Ni, and V were previously determined by X-ray fluorescence. Representative analyses are given in Table 1. All other reported trace elements were determined by inductively coupled plasma-mass

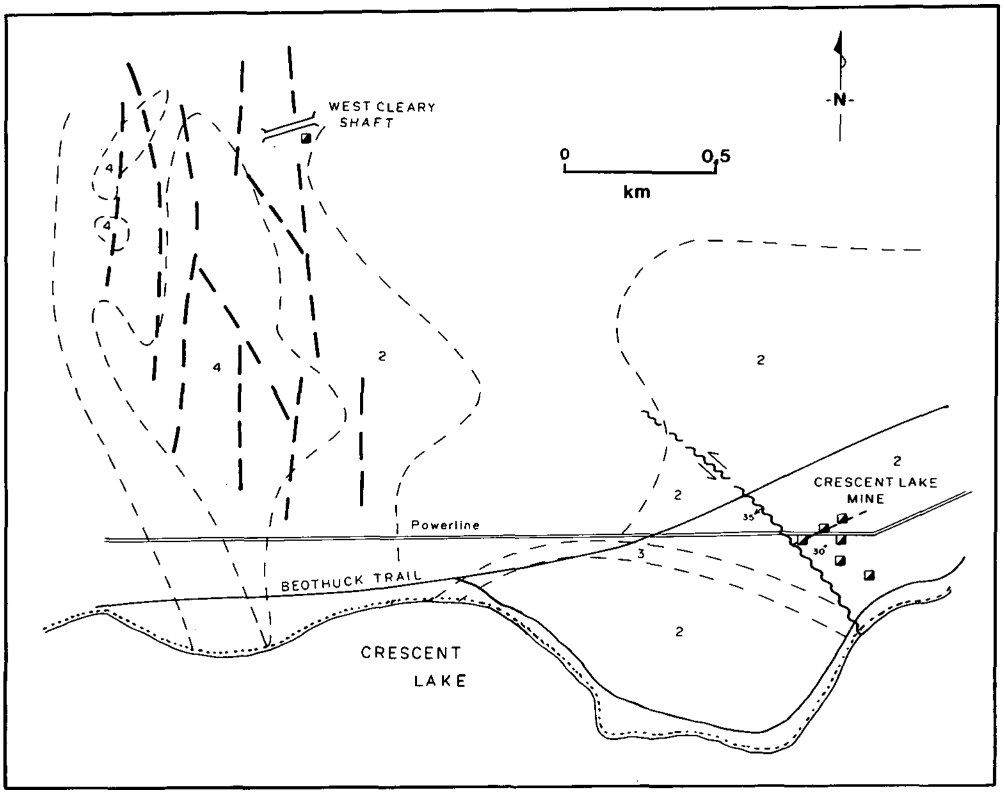

Fig. 2. Geology of the Crescent Lake Mine area. The heavy dashed lines represent the mineralized vein system. 1 - hematitized pillow lava, pillow basalt; 2 - non-hematitized pillow lava; 3 - red argillite, siltstone, chert; 4 - West Cleary pluton, subvolcanic gabbro, granodiorite. Location of old shafts indicated by half-closed squares (after MacQuarrie, 1976; Swinden *et al.*, 1988).

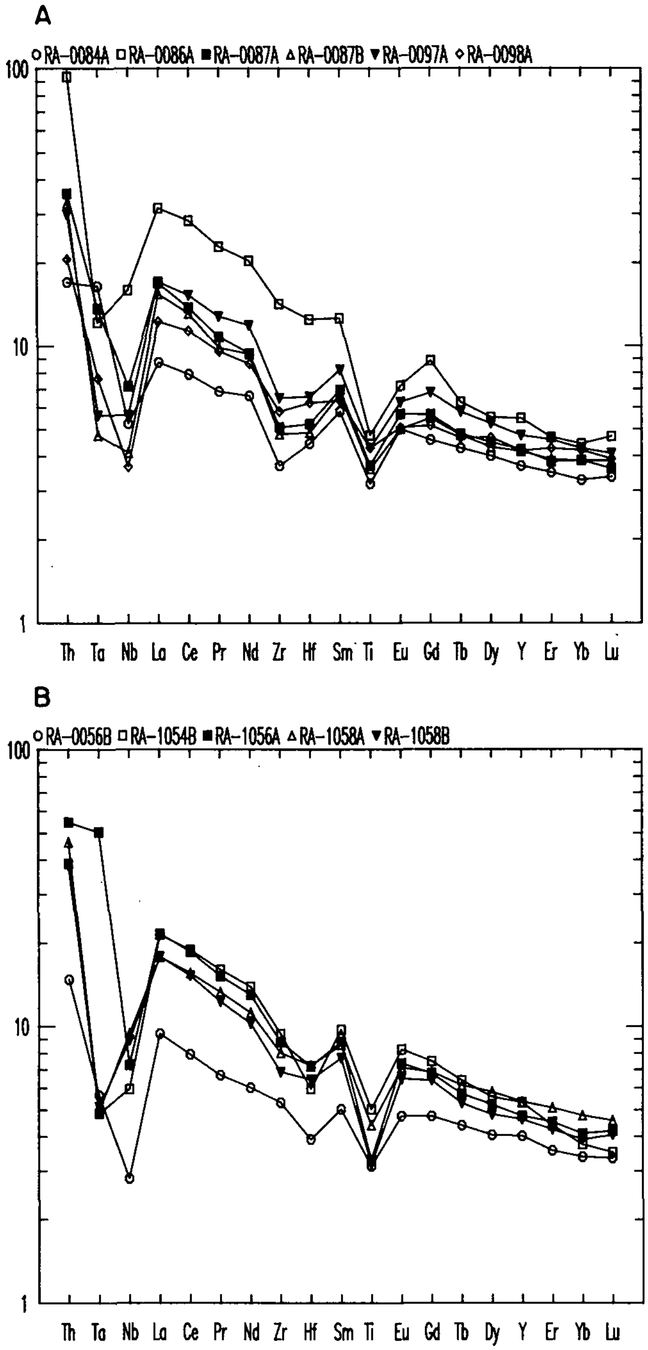

Fig. 3. Rare earth and trace element plots (chondrite-normalized) for Robert's Arm volcanic rocks in (A) Crescent Lake area, and (B) Pilley's Island area, indicating calc-alkalic affinity and similarity between the two regions.

Table 1. Mafic volcanic whole rock analyses from the Crescent Lake (RA-87) and Pilley's Island (RA-1058) Mines. Recalculated to 100% anhydrous.

	RA-87A	RA-87B	RA-1058A	RA-1058B
SiO_2 %	52.71	54.00	51.53	46.70
TiO_2	0.70	0.68	0.83	0.60
Al_2O_3	15.43	14.65	16.51	15.23
FeO	8.77	7.64	8.00	5.42
MnO	0.17	0.16	0.11	0.17
MgO	8.39	7.54	7.09	5.48
CaO	9.11	9.63	10.57	23.64
Na_2O	4.56	5.44	2.86	1.70
K_2O	0.01	0.10	2.27	0.85
P_2O_5	0.14	0.16	0.23	0.20
Cr ppm	367	395	242	186
Ni	136	144	68	44
V	267	271	204	148
Cu	92	92	2	11
Pb	0	0	6	3
Zn	58	61	54	43
Rb	1	1	57	17
Ba	96	115	301	147
Sr	203	200	158	145
Ta	0.55	0.19	0.2	0.21
Nb	4.6	2.7	6.1	5.8
Hf	1.46	1.36	2.02	1.8
Zr	50	47	79	67
Y	16	16	21	18
Th	3.14	2.9	4.08	3.37
La	10.65	9.74	11.24	11.26
Ce	21.84	20.81	24.68	24.18
Pr	2.71	2.47	3.34	3.09
Nd	11.42	11.33	13.56	12.39
Sm	2.77	2.67	3.42	3.08
Eu	0.85	0.75	1.06	0.97
Gd	3.01	2.93	3.65	3.4
Tb	0.47	0.46	0.6	0.51
Dy	2.96	2.84	3.83	3.17
Er	1.65	1.68	2.19	1.83
Yb	1.71	1.7	2.11	1.72
Lu	0.24	0.25	0.3	0.27

spectrometry at Memorial University of Newfoundland. Analytical methods and estimates of accuracy and precision are in Bostock (1988) and Jenner *et al.* (1990).

The data show that TiO_2 in mafic volcanic rocks north of Crescent Lake and in the Pilley's Island area does not increase with fractionation, a feature characteristic of calc-alkalic magma series (Miyashiro and Shido, 1975). The extended REE patterns in Figure 3a and b show that these rocks are moderately enriched in the light REE, also typical of calc-alkalic volcanics, and have distinctive positive Th and negative Nb anomalies on a chondrite-normalized basis, indicating that they were erupted in an island arc environment (e.g., Sun, 1980). Most have slight negative TiO_2 anomalies, perhaps indicating crystallization of an iron-bearing phase such as iron oxides or amphiboles, again consistent with a calc-alkalic fractionation series.

These data suggest that the Crescent Lake and Pilley's Island volcanic rocks are very similar geochemically and that Crescent Lake Mine occupies the structural base of a more or less continuous calc-alkaline sequence which culminates with widespread felsic volcanism and local volcanogenic sulphide deposition in the Pilley's Island area.

Deposit geology

According to Espenshade (1937), the composite quartz vein system at the Crescent Lake Mine was exposed in outcrop for about 60 m over a width of 1.0-4.5 m (Fig. 2). The mineralized veins are fissure-type within spilitized calc-alkalic basaltic flows and breccias (Bostock, 1988). Sulphide minerals in the quartz include chalcopyrite and pyrite, with minor sphalerite, galena, and covellite. Additional small quartz veins of similar mineralogy occur near the main vein. Espenshade (1937) reported a 76-cm thick mass of chalcopyrite along the footwall of the main vein. Silver values of 10-20 g/tonne have been reported from the mine dumps (Howse and McArthur, 1977).

Analyses of representative grab samples from the mine area (Table 2) show that Cu is elevated in almost all samples, while Zn and Pb are sporadic. Gold and its tracers As and Sb tend to follow Cu. The highest grade sample, #228E, with 5.6% Cu, contains anomalous Au, Ag, As, and Sb, though not of economic grade.

The mineralized quartz veins are commonly sheeted, suggesting repeated opening and filling of the veins (crack-seal mechanism; Ramsay, 1980) and are locally brecciated and contain inclusions of chloritized wallrock. Base metal sulphides are restricted to the quartz vein material and locally comprise up to 15% by volume, although average considerably less (Swinden, 1987). Widespread wallrock alteration associated with the veins consists of pervasively chloritized, silicified, and pyritized basalt with local quartz-sericite alteration. Chlorite within the mineralized veins has a distinctive dark green to black colour (Swinden, 1987), similar to VMS stockworks such as the Ansil Mine in Quebec (G. Riverin, personal communication, 1990).

MINERALOGY, TEXTURES, AND PARAGENESIS

The veins contain quartz, pyrite, chalcopyrite, sphalerite, galena, iron oxide, covellite, and newly recognized carrollite. The sulphides and oxides occur in five discernible paragenetic stages (Fig. 4), established on the basis of textural relationships of ore and gangue minerals observed during this study: pre-ore sulphide stage 1; ore sulphide stages 2 and 3; post-ore sulphide stage 4; and a later oxidized stage 5.

Quartz appears to occur in the first four stages although it is not possible to identify a distinctive quartz for each distinctive paragenetic stage. However, the quartz veins display sheeting, interpreted to be a crack-seal texture caused by episodic pressure fluctuation and injection of fluids (Ramsay, 1980; Sibson, 1981), forming multiple generations of quartz.

Pyrite is found in silicified and chloritized wallrock and within the quartz veins where it generally forms 1-7 mm subhedral crystals which are fragmented or "crackled" (Fig. 5a). This pyrite appears to precede formation of base-metal sulphides and is classified as stage 1. The crystal fragments show little movement or rotation to indicate severe tectonism, and the crackling may be the result of the multiple crack-seal cycles. Pyrite also occurs as unbrecciated subhedral grains (0.5-3 mm), anhedral masses, and rare euhedral cubic crystals (0.1 mm). Stage 1 pyrite may contain cross-cutting veinlets of chalcopyrite (Fig. 5e) and occur as brecciated fragments surrounded by stage 2 sphalerite (Fig. 5b). There is no petrographic evidence to suggest that pyrite is coeval with sphalerite or chalcopyrite even though sulphur isotope values suggest that stage 1 pyrite could have formed in isotopic equilibrium with stage 3 chalcopyrite (discussed later). A second generation of pyrite mantles chalcopyrite and replaces chalcopyrite and sphalerite along fractures and is classified as post-ore, stage 4 pyrite (Fig. 5f).

Along with galena, sphalerite appears to be the first base-metal sulphide formed and is classified as stage 2. It can occur as small (0.1-3 mm), isolated, and irregular aggregates but more commonly it is intimately associated with chalcopyrite. It is almost always partially replaced by chalcopyrite to form the texture characteristic of "chalcopyrite disease" (Fig. 5d). The diseased sphalerite contains 1-20 μm wide veinlets and round inclusions of replacement chalcopyrite formed when copper-rich fluids reacted with pre-existing sphalerite (Barton, 1978).

Galena occurs in stage 2 as anhedral blebs and irregularly shaped patches in contact with diseased sphalerite and chalcopyrite. Intergrown contacts between galena and diseased sphalerite suggest that they are coeval. Galena infills fractures in quartz and is attached to a pyrite grain which is mantled by iron-oxide (Fig. 5c).

Chalcopyrite occurs dominantly as small (1-8 mm), isolated anhedral patches, but also cross-cuts and infills fractures in stage 1 pyrite (Fig. 5e). Chalcopyrite was also observed to have replaced stage 2 sphalerite as fine inclusions and veinlets (Fig. 5d) and is thus classified as stage 3. Barton and Bethke (1987)

Table 2. Geochemical analyses of mineralized grab samples from the Crescent Lake Mine.

Spl. No.	228A	228B	228C	228D	228E	228F	228G
Cu %	2200	1400	1100	2900	56000	8900	180
Pb	40	8	12	16	120	22	28
Zn	110	79	180	4800	670	170	210
Au ppb	2	3	<1	1	74	7	3
Ag ppm	0.5	<.5	<.5	0.5	50	4	<.5
As	130	74	36	110	570	200	60
Sb	0.7	0.5	<.1	1.1	8.2	0.5	0.3
Ni	170	130	270	65	230	7	600

Stage	1	2	3	4	5
pyrite	X			X	
sphalerite	X				
galena		X			
chalcopyrite			X		
carrollite			X		
covellite					X
iron oxides					X

Fig. 4. Mineral paragenesis at the Crescent Lake deposit inferred from petrographic relationships. Separate pyrite-forming sulphide stages (1 and 4) occur prior and subsequent to the copper-lead-zinc sulphide-forming event (stages 2 and 3). A post-sulphide stage (5) in which iron oxides (and covellite) formed indicates a later oxidizing, likely weathering, event.

concluded that chalcopyrite disease occurs in moderate temperature (200-400°C) deposits that are formed and "quenched" rapidly. Stage 2 sphalerite and galena and stage 3 chalcopyrite may therefore be close in time or even partly coeval. Small amounts of Au, Ag, As, and Sb, which correlate with copper content (Table 2), were likely introduced in stage 3 fluids.

Iron oxide mantles earlier pyrite (Fig. 5c), chalcopyrite, and diseased sphalerite, and occurs as fracture fillings in quartz. The timing of the iron-oxide replacement is unclear but its presence indicates that a period of oxidation followed sulphide formation. A notable feature of this oxide is its spongy, cellular texture which is seen in all but the narrowest of veinlets. Colloform growth-banding can be seen in several open fractures where the iron oxide grew by precipitation inwards from the walls of fractures.

Covellite (CuS) replaced diseased sphalerite preferentially, leaving the chalcopyrite inclusions as islands within covellite. Replacement occurred along fractures (Fig. 5d) and at grain boundaries with total replacement seen only in the smallest (0.1-0.5 mm) sphalerite grains. Timing of the covellite replacement is unclear but it possibly formed during the same oxidizing conditions as the iron oxide (stage 5).

An unknown, yellow-white mineral was identified as carrollite [$(Cu,Ni)Co_2S_4$] of composition 10.8% Cu, 10.8% Ni, 38.9% Co, 0.6% Fe, and 41.6% S by microprobe analysis at the University of Toronto. It occurs as small (20 µm) separate grains or compact masses enclosed within chalcopyrite, similar to textures described by Ramdohr (1969) for carrollite in hydrothermal vein systems. About ten individual grains of carrollite were observed in only one sample collected from the mine dump.

FLUID INCLUSION STUDY

Sample selection

In order to obtain temperatures of ore formation, vein quartz intimately associated with base-metal sulphides was used for fluid inclusion analysis. Clear quartz was selected where possible because it is generally less fractured and contains fewer secondary fluid inclusions than cloudy quartz. Severely fractured samples were rejected. Twenty slabbed surfaces were examined to obtain several ages of quartz, but no cross-cutting relationships were observed. The clearest material and the quartz that yielded the most useable inclusions was found immediately adjacent to ore sulphides, and thus is more likely coeval. Therefore, even though the relative age of quartz could not be discerned, ore-stage quartz was probably sampled preferentially.

Description and classification

Quartz veins from Crescent Lake contain visible fluid inclusions of 1-5 µm size with the majority <3 µm. This small size made the critical phase changes during freezing and heating difficult to observe and limited the number of measurements obtainable. The error in measurement is thus limited by the accuracy of the observer rather than the instrumentation.

Only halite-undersaturated, aqueous liquid-vapour type inclusions were observed in this study. They homogenize by expansion of the liquid and disappearance of the vapour phase upon heating (Fig. 5g). No daughter minerals and no other gases or liquids such as CO_2 were observed. The range in volume percentage of the vapour phase in the inclusions was visually estimated at 3-8 vol. % (Roedder, 1984). No wide variation in vapour/liquid ratios in coeval inclusions, which otherwise would indicate boiling, was observed.

The inclusions are also classified chronologically as primary, secondary, or pseudo-secondary (Roedder, 1984). The repeated fracturing of the quartz noted earlier is evident from the abundant planes of fluid inclusions along healed fractures. These pseudo-secondary inclusions represent fluids present during subsequent crack-seal cycles, and are therefore possibly ore-stage. However, they cannot be distinguished from secondary inclusions along later healed fractures. Primary inclusions occur in planes along crystal growth zones, but in this study, these are too small (<1 µm) to be used. Single, isolated inclusions in this study are also considered primary. Inclusions showing evidence of necking or leakage (Roedder, 1984) were rejected.

Equipment and methodology

Temperatures of phase changes in fluid inclusions were measured with a chromel-constantan thermocouple attached to a Doric 410A digital trendicator with a Fluid Inc. gas-flow heating/freezing system. The equipment was calibrated using synthetic fluid inclusion standards (pure H_2O and pure H_2O+CO_2) provided by Fluid Inc. Temperature variations within the heating stage are <0.1°C at -56.6°C and 0.0°C, and less than 1°C at 290°C.

Doubly polished sections (80-100 µm thick) were examined prior to measurement, and the type, size, shape, distribution, vapour phase volume, and relationship of inclusions with respect to sulphides recorded. Inclusions suitable for further study were noted and 3-7 mm size chips removed from the polished plate for measurement. Each inclusion was subjected to several freezing and heating runs to minimize errors. An average temperature was recorded for each inclusion.

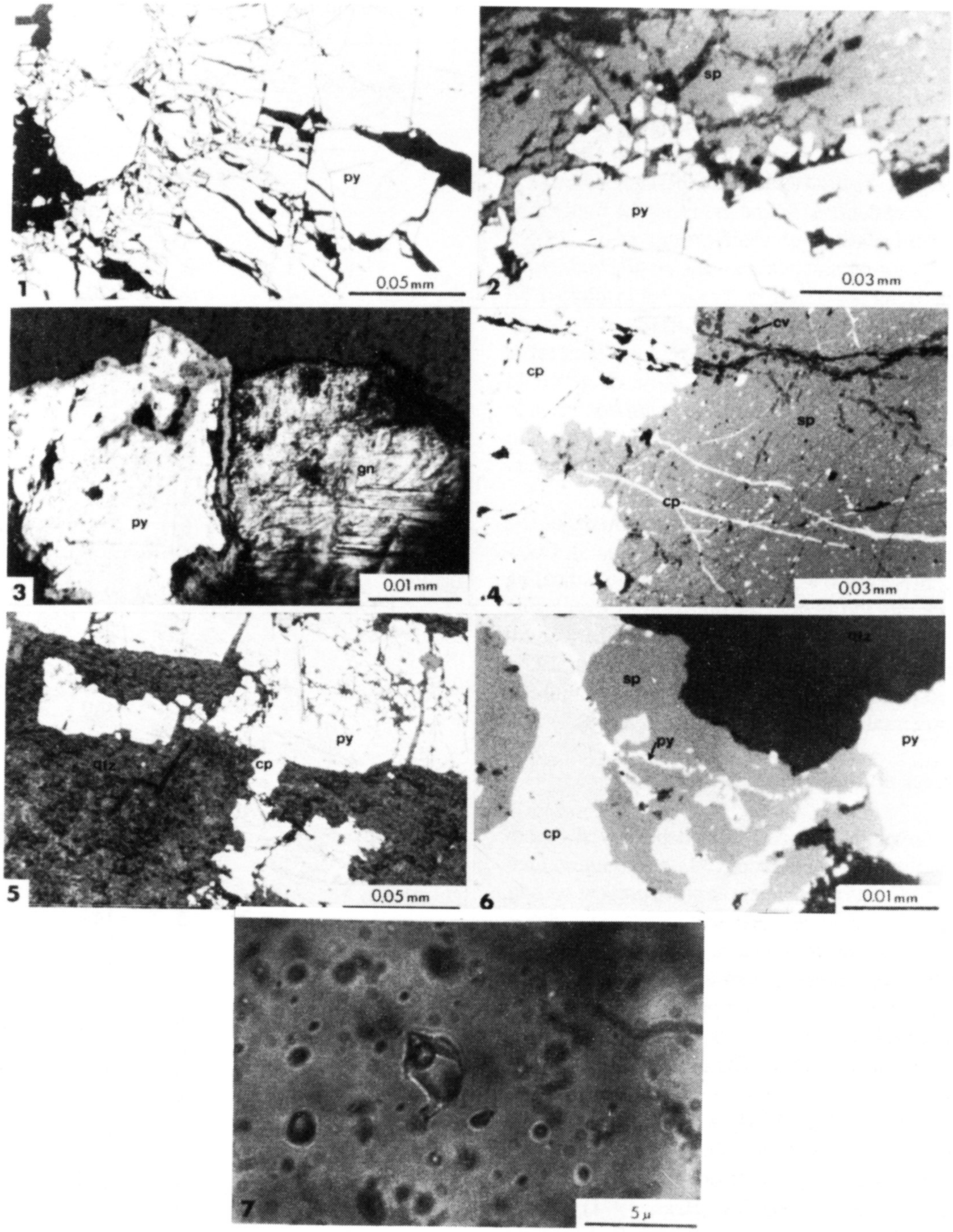

Fig. 5. (1) Earliest sulphide (stage 1) is crackled pyrite (py). $\partial^{34}S_{py}$ = 5.0-6.2 ‰. (2) Brecciated fragments of stage 1 pyrite (py) incorporated into later stage 2 sphalerite (sp). $\partial^{34}S_{sp}$ = 2.3 ‰. (3) Mantling of pyrite (py) grain by stage 5 iron oxide adjacent to a grain of stage 2 galena (gn). (4) Randomly orientated blebs and veinlets of chalcopyrite (cp) in stage 2 sphalerite (sp) (chalcopyrite disease). Covellite (cv) (stage 5?) replaces sphalerite (sp) along fractures. Note also the concave grain boundaries between chalcopyrite and sphalerite. $\partial^{34}S_{cp}$ = 2.2-3.4 ‰. (5) Fractured stage 1 pyrite (py) cut by a later vein of stage 3 chalcopyrite (cp). Consistent isotope fractionation between stage 1 pyrite and stage 3 chalcopyrite suggests equilibrium, but because the sulphides are not coeval, a more likely explanation is that sulphur source was fairly constant with time. (6) Chalcopyrite diseased stage 2 sphalerite (sp) and stage 3 chalcopyrite (cp) cut by a later, post-ore stage 4 pyrite (py) introduced along a fracture. (7) Primary fluid inclusion in quartz containing aqueous liquid and vapour. Homogenization temperatures range widely between 112° and 250°C. Salinities range narrowly between 3.3 and 6.6 wt. % NaCl equivalent.

Microthermometry results

During heating, the separate liquid and vapour phases become one at the homogenization temperature (T_h); in this study the diminishing vapour bubble disappeared into the liquid phase. The T_h were uncorrected for pressure and therefore provide an estimate of the minimum temperature of formation (Roedder, 1984). During freezing, the final melting temperature of ice (T_m) gives the freezing-point depression and therefore the fluid salinity as weight percent NaCl equivalent (Potter *et al.*, 1978). Detailed results of freezing and heating runs on 40 fluid inclusions from quartz veins are given in Table 3 and plotted on histograms (Figs. 6, 7). Homogenization temperatures for quartz (Fig. 6) range widely between 112 and 250°C with noticeable clusters at 130-140° and 200-220°C. This wide range could reflect a protracted quartz- and ore-forming event over a wide temperature range at constant pressure, or alternatively, could result from a wide range of fluid pressures at constant temperature (see below).

Measurements of T_m were hindered by the small size of the inclusions, and not all samples have T_m values (Table 3). Compositions range from 3.3 to 6.6 wt. % NaCl equivalent, indicating a fairly constant salinity throughout the ore-forming event (Fig. 7). These temperatures and salinities are similar to the Kuroko stockwork and related Cu-Pb-Zn veins (Hattori and Sakai, 1979; Pisutha-Arnond and Ohmoto, 1983), but higher than the 0-3% salinities of mesothermal gold deposits (Roberts, 1988).

Genetic significance of fluid inclusion data

The fluids that formed the Crescent Lake deposit were homogeneous, slightly saline brines, without CO_2, at minimum temperatures of 112-250°C, and at sufficient depth to prevent boiling. The field evidence of successive crack-seal cycles (Swinden *et al.*, 1988) does not resolve the constant pressure or constant temperature question, but rather is permissive with either. The crack-seal evidence indicates that fluid pressures certainly did fluctuate; from near-lithostatic just prior to cracking to near-hydrostatic when the crack opened. The absence of coexisting vapour-dominant inclusions in the vein system suggests that boiling did not occur (Roedder, 1984) when pressure was released. For a fluid at 250°C with a salinity of 5 wt. % NaCl equivalent, a fluid pressure of 3.9 MPa or a minimum depth of 428 m is necessary to prevent boiling (Haas, 1971). Quartz formed at higher fluid pressures would yield a T_h far below the real trapping temperature.

Table 3. Primary fluid inclusion data from Crescent Lake quartz veins.

Sample	Size µm	Vapour %	T_h °C	T_m °C	Salinity %NaCl
CL 1					
1	5 x 2	4	228	-3.2	5.2
2	4 x 2	3	182		
3	4 x 3	3	140	-3.5	5.7
4	4 x 4	5	220	-2.0	3.3
5	3 x 2	4	136		
6	3 x 1	4	220		
7	3 x 3	3	190		
8	5 x 3	5	160	-4.1	6.6
9	2 x 3	5	187		
10	3 x 3	5	130		
11	5 x 4	8	250	-3.4	5.5
12	4 x 4	4	202	-2.6	4.3
13	4 x 4	5	200	-3.6	5.8
14	5 x 5	4	208	-2.8	4.6
CL 2					
1	4 x 2	3	211		
2	4 x 3	5	142	-3.0	4.9
3	4 x 4	4	200	-4.0	6.4
4	2 x 2	6	189		
5	2 x 2	4	195		
6	3 x 2	3	179		
7	2 x 2	3	218		
8	4 x 3	5	150	-2.4	4.0
9	4 x 3	4	212	-3.3	5.4
CL 4					
1	4 x 2	5	141		
2	4 x 3	4	134	-2.1	3.5
3	3 x 3	5	113		
4	4 x 3	5	202	-3.5	5.7
5	4 x 3	5	125	-4.0	6.4
6	2 x 2	4	132		
7	4 x 3	4	112	-4.1	6.6
8	3 x 2	5	190		
9	3 x 3	6	215		
10	5 x 3	5	203	-2.9	4.8
11	4 x 3	4	208	-4.0	6.4
12	3 x 2	3	230		
CL 5					
1	4 x 2	3	189		
2	2 x 2	4	124		
3	4 x 3	4	211	-3.2	5.2
4	3 x 3	4	207	-3.6	5.8
5	3 x 2	5	218	-4.0	6.4

MINERAL CHEMISTRY

Analytical method

All mineral compositions were determined from polished sections by energy dispersive electron microprobe analysis at the University of Toronto. An Etec Autoprobe equipped with a Li-drifted Kevex Si detector and "on-line" data reduction using a "peak stripping" program was used (C. Cermignani, personal communication, 1989). Accelerating voltage was 20 kV with a beam current of 0.120 nA. Intensity calibration was performed on Co metal with 100 second (live time) for all analyses. Two mineral grains were analyzed from each sample with good reproducibility. Standards approximating each uncalibrated mineral analysis were used as follows: natural chlorite for Si, Al,

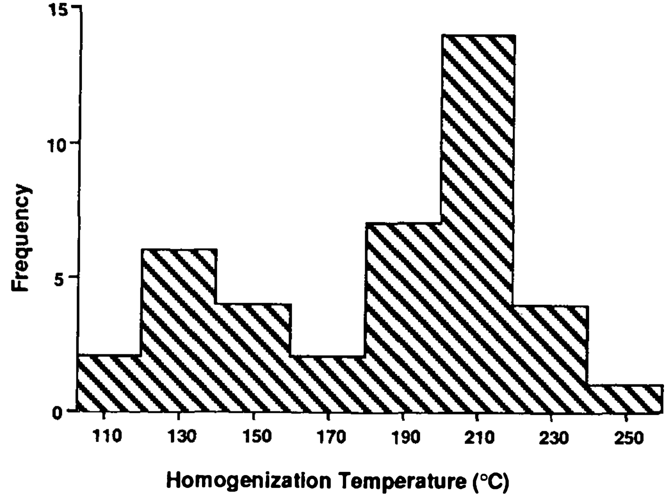

Fig. 6. The wide range of homogenization temperatures of primary fluid inclusions from Crescent Lake vein quartz related to sulphide deposition (Table 3) reflects either the actual range in formation temperatures at constant pressure, or fluctuating fluid pressures during the episodic crack-seal cycles of the veins.

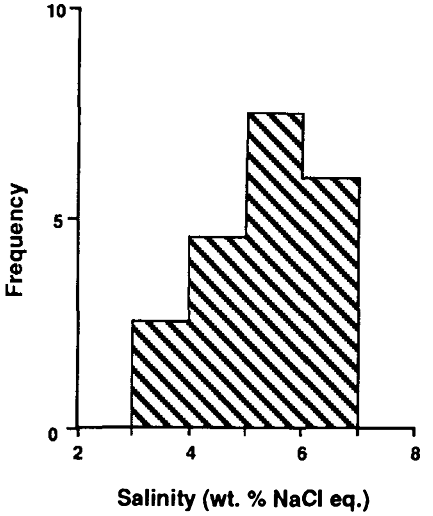

Fig. 7. The narrow range of melting temperatures of primary fluid inclusions from vein quartz (Table 3) indicate relatively constant salinities of the Crescent Lake hydrothermal fluids in the range of 3-7 wt. % NaCl equivalent. No daughter crystals or gases such as CO_2 were found.

Fe, Mn, and Mg in all chlorite analysis; natural sphalerite for Zn, Fe, and S in the sphalerite anaylsis; and Co metal for Co, natural chalcopyrite for Cu, Fe, and S, and natural millerite for Ni in the carrollite analysis.

Chlorite analyses

Chlorites were analysed in order to differentiate between ore-bearing and indigenous chlorite in the host rock. Chlorite adjacent to the veins and in country rock 50 m away in an area of barren quartz-epidote-feldspar veins was sampled. Results are shown in Table 4. The structural formulae are calculated on the basis of 28 oxygens, and Al^{IV} and Al^{VI} values have been determined based on 8 Si+Al^{IV} (Deer *et al.*, 1962). The microprobe does not distinguish between divalent and trivalent iron, but typically 95% of iron in chlorite is ferrous (Cathelineau and Nieva, 1985).

Sulphide-associated chlorite at Crescent Lake has a higher Fe/Fe+Mg ratio (~ 0.51) than chlorite associated with barren veins (~ 0.42) (Table 4). Several thin sections from mineralized quartz veins at Crescent Lake contain chlorite with a distinctive blue birefringence, characteristic of chlorites with high Fe/Fe+Mg ratios (Saggerson and Turner, 1982; Kranidiotis and MacLean, 1987). Similar Fe-rich chlorites occur in other Cu deposits in Robert's Arm volcanic rocks (Bachinski, 1976).

Chromium occurs in sulphide-associated chlorite but not in the barren zone (Table 4). Although Pilley's Island chlorite is interpreted as Mg-rich (without analyses), they are Cr-rich like Crescent Lake and also contain anomalous Ni and Co (Bowles, 1987). The presence of carrollite at Crescent Lake indicates that Cr-Co-Ni-bearing fluids were responsible for both deposits—a possible genetic link.

Genetic significance of chlorite compositions

For chlorites in the Si-Al-Mg-Fe system, Fe substitutes extensively for Mg, providing a tool to differentiate between chlorites formed from Mg-rich and Fe-rich hydrothermal fluids. The Fe/Fe+Mg ratio of a fluid may vary because of (1) the source of the fluid (i.e., Mg-rich seawater or Fe-rich metamorphic or juvenile water); (2) the history of reaction with the host rock [i.e., extensive reaction of Mg-rich seawater with basalt produces an Fe-rich fluid (Seyfried and Bischoff, 1981)]; or (3) mixing of fluids of different compositions. Chlorites from the Crescent Lake deposit are relatively Fe-rich, suggesting that the fluids are either juvenile or highly reacted seawater.

The presence of Cr is not uncommon in chlorites because Cr^{+3} may substitute for Al^{+3} (Foster, 1962). The Cr may have been leached either from an ultramafic body, or from magnetite during sulphidization reactions between the basaltic host rocks and sulphur-rich fluids to form pyrite.

Chlorite geothermometer

The method of Cathelineau and Nieva (1985), which correlates Al^{IV} content of chlorite with independently calculated and measured temperatures, was applied to the Crescent Lake chlorites. Kranidiotis and MacLean's (1987) equation:

$$T^{\circ}C = 106Al^{IV} + 18 \qquad (1)$$

was used, with their correction for varying Fe/Fe+Mg ratios changed to the general relation:

$$Al^{IV} \text{ corrected} = Al^{IV} \text{ sample} - 0.7\{(Fe/Fe+Mg) - 0.3\} \qquad (2)$$

Kranidiotis and MacLean (1987) recommend its use in low-pressure (<100 MPa) and non-metamorphosed environments only, conditions which appear applicable to the Crescent Lake

Table 4. Microprobe analyses of chlorites from the Crescent Lake area.

	Ore Zone CRL 11		Barren Zone CRL 10	
Wt. % Oxides				
SiO_2	27.24	26.69	29.13	30.14
Al_2O_3	17.96	19.19	16.32	14.23
Cr_2O_3	1.92	0.65	0.00	0.00
FeO	25.85	25.61	22.68	22.17
MnO	0.64	0.32	0.19	0.29
MgO	14.41	13.70	17.45	17.87
Total	88.02	86.17	85.78	84.70
Structural Formulae (28 oxygens)				
Si	5.77	5.74	6.17	6.45
Al^{iv}	2.23	2.26	1.83	1.55
Al^{vi}	2.26	2.61	2.24	2.04
Cr	0.32	0.11	0.00	0.00
Fe	4.58	4.61	4.02	3.97
Mn	0.12	0.06	0.03	0.05
Mg	4.55	4.39	5.51	5.70
Fe/Fe+Mg	0.50	0.51	0.42	0.41

deposit. Another condition assumed by Kranidiotis and MacLean (1987) is that the chlorites are Al-saturated for equation 1 to apply. On a Hey (1954) diagram, the ore-stage chlorites are more Al-rich than the barren chlorites and plot within the field used by Kranidiotis and MacLean (1987), but are Al-undersaturated, even though sericite is found in the alteration (Swinden, 1987). However, because the Los Azufres data (Cathelineau and Nieva, 1985) used to determine equation 1 are similarly Al-undersaturated, we will assume that equation 1 can be used to estimate formation temperatures of the Crescent Lake chlorites.

Average formation temperatures of 240°C (s=2°) for sulphide-associated chlorites are obtained, comparing well with the fluid inclusion homogenization temperatures of 112-250°C in mineralized quartz veins. The hydrothermal chlorite temperature of 240°C is near the high end of the T_h range and because it is pressure-independent, may provide a better estimate of the true trapping temperature: the wide range of T_h's obtained may only reflect fluctuations in crack-seal fluid pressures, as mentioned earlier.

A revised relationship between Al^{IV} and temperature was obtained by Cathelineau (1988), using the combined field data from the Los Azufres geothermal and Salton Sea (McDowell and Elders, 1980). With the exception of two points, both data sets appeared compatible and gave the relation:

$$T°C = 321.98Al^{IV} - 61.92 \qquad (3)$$

(Al^{IV} based on 14 oxygens) for a temperature of 300°C (s=4°) for the ore zone chlorites, significantly higher than the 240°C temperature calculated above. However, because the Al^{IV} variation with Fe/Fe+Mg content (equation 2) is not considered in equation 3, we assume that 240°C is closer to the real formation temperature of the Crescent Lake hydrothermal chlorites.

Sulphide analysis

Microprobe analysis of Fe in chalcopyrite-diseased sphalerite was carried out at the University of Toronto. Copper was analyzed simultaneously with iron and zinc in the sphalerite, and the amount of chalcopyrite-bound Fe (Cu/Fe = 1; Yund and Kullerud, 1966) subtracted to obtain the Fe content in sphalerite. Calculated values for Crescent Lake sphalerite range between 4.7 and 5.6 mole-% FeS, outside the <1 mole-% FeS range of Kuroko stockwork veins (Bryndzia *et al.*, 1983) but within the range of associated Cu-Pb-Zn veins (Hattori and Sakai, 1979).

SULPHUR ISOTOPES

Samples and methodology

Thirteen sulphide separates, including 7 chalcopyrite, 1 diseased sphalerite, and 5 fractured pyrite, were obtained from 20 polished slabs for sulphur isotope measurements to determine geochemical conditions and possible sources of sulphur. The chalcopyrite and sphalerite separates were drilled and measured directly; gangue contamination in the 5 pyrite separates was removed by the nitric acid-bromine oxidation method (Thode *et al.*, 1961) to form barium sulphate. Isotope analyses were measured on a VG mm602C mass spectrometer at the National Hydrological Research Institute by J. Nriagu.

Sulphur isotope results

Crescent Lake sulphides have positive (^{34}S-enriched, or isotopically heavy) values compared to the Canon Diablo troilite standard (Table 5). The $\partial^{34}S$ ranges are narrow for each mineral: pyrite, 5.0-6.2 ‰; chalcopyrite, 2.2-3.4 ‰; the single sphalerite value is 2.3 ‰, or 2.2 ‰ when corrected for chalcopyrite content. These values are much lighter than the minimum value of 11-12 ‰ expected in volcanogenic sulphides derived from 29 ‰ Early Ordovician seawater sulphate (Sangster, 1968; Claypool *et al.*, 1980), but similar to the 2.5-7.6 ‰ range from the Gull Pond copper-bearing stockwork, also in Robert's Arm volcanic rocks (Bachinski, 1978).

Fractionation beween sulphide minerals in isotopic equilibrium enriches ^{34}S in the order: pyrite > sphalerite > chalcopyrite > galena (Kyser, 1987). The pyrite and chalcopyrite values from Crescent Lake agree with this trend (Table 6). (Sphalerite is always contaminated with chalcopyrite, and galena is too fine grained to be separated.) Fractionation between pyrite and chalcopyrite from the same samples is constant ($\Delta_{py-cp} \approx 2.7$), suggesting isotopic equilibrium even though they are of different paragenetic ages (Fig. 4). Pyrite-chalcopyrite pairs from 3 samples

Table 5. Sulphur isotope analyses from Crescent Lake Mine.

Sample	Mineral	∂^{34}S (°/oo)
CRL 6	pyrite	5.2
CRL 6	pyrite	5.5
CRL 11	pyrite	5.4
CRL 12	pyrite	5.0
CRL 15	pyrite	6.2
CRL 1	chalcopyrite	3.4
CRL 1	chalcopyrite	3.3
CRL 6	chalcopyrite	2.7
CRL 11	chalcopyrite	2.8
CRL 12	chalcopyrite	2.3
CRL 12	chalcopyrite	2.3
CRL 12	chalcopyrite	2.2
CRL 6	sphalerite (cp)	2.3

yield consistent sulphur isotope temperatures of 133-140°C (table 10 in Ohmoto and Rye, 1979), within the range of homogenization temperatures from fluid inclusions. Isotopic temperatures from one pyrite-sphalerite pair and one chalcopyrite-sphalerite pair are anomalously low, suggesting either isotopic disequilibrium or an unrepresentative sphalerite value. No ∂^{34}S values are available from Pilley's Island, but Gull Pond sulphides have a similar range (2.5-7.6 ‰) as Crescent Lake (Bachinski, 1978).

Genetic significance of ∂^{34}S values

The ∂^{34}S values of sulphides depend upon the physical and chemical conditions of the ore-forming fluid (T, pH, fO_2, etc.), bulk sulphur isotope composition, and the amount of interchange between the fluid and country rock (water/rock ratio) (Ohmoto, 1986). If isotopic equilibrium exists between the sulphide minerals and thus with the ore-forming fluid, general inferences about sulphur source, formation temperatures, and geochemical environment can be made.

For coeval sulphides, isotopic equilibrium suggests an abundance of sulphur available in the fluid. In the case of Crescent Lake, even though the sulphides are not coeval, the conformity with the equilibrium fractionation trend, coupled with the narrow ranges, suggests a homogeneous sulphur supply of consistent composition throughout the ore-forming process. Any mixing of fluids was thoroughly completed by the time it reached the vein system.

DISCUSSION OF CHARACTERISTICS AND GENESIS

Summary of deposit characteristics

Our petrographic, geochemical, and isotopic data provide some constraints on the nature and origin of the Crescent Lake deposit. The mineralization comprises sheeted (crack-seal) quartz veins with chalcopyrite and pyrite, and lesser sphalerite and galena. Vein opening occurred in a tensional regime; there is no evidence of shearing or faulting associated with the vein formation and mineralization. Copper is the dominant mineral of economic interest, although zinc and silver are locally anomalous. Geochemical anomalies in Pb, As, Sb, and Au also occur.

Minor hydrothermal chlorite and altered rock inclusions occur in the quartz veins, and a narrow halo of chlorite-pyrite alteration exists around the veins. The sulphide and oxide minerals were deposited with quartz in five paragenetic stages: pyrite; galena-sphalerite; chalcopyrite; pyrite; and covellite-iron oxide.

Homogenization temperatures of ore-stage quartz are wide-ranging (112-250°C) with peaks at 130-140°C and 200-220°C. This bimodality may reflect pressure fluctuations during repeated vein opening, and the pressure-independent chlorite crystallization temperature of 240°C being closer to the true trapping temperature. No evidence of boiling is seen, requiring a minimum formation depth of ~ 430 m. No CO_2 is present. Salinities range narrowly between 3.3 and 6.6% NaCl equivalent.

Analyses of hydrothermal chlorite indicate an Fe- rather than Mg-rich fluid. The ∂^{34}S values of 2.2-6.2 ‰ are similar to both VMS and Archean lode gold deposits (Franklin *et al.*, 1981; Roberts, 1988) but indicate that some sulphur was derived from the host volcanics. Isotopic disequilibrium between coeval mineral pairs but apparent equilibrium between non-coeval pyrite and chalcopyrite suggests a homogeneous sulphur source over the duration of the hydrothermal system rather than high sulphur activity.

Genetic models

The Crescent Lake deposit is clearly epigenetic with respect to its host rocks, a feature expected for both VMS stockwork zones and for later mineralization related to tectonism or intrusion. Although mesothermal gold veins are widespread in the Robert's Arm Group (Hudson and Swinden, 1989, 1990), a number of features argue against a mesothermal origin for the Crescent Lake deposit: (1) the lack of associated shearing and deformation; (2) dominant Cu-Pb-Zn-Ag mineralogy with minor Au, As, and Sb; (3) lack of carbonate minerals in the veins and alteration zones; and (4) lack of CO_2 in fluid inclusions and salinities higher than the 0-3% typical of mesothermal gold deposits.

The mineralization is more consistent with a volcanogenic origin as suggested by Dean (1977). The quartz and sulphide paragenesis of the Crescent Lake deposit is consistent with that found in the Kuroko stockworks (Pisutha-Arnond and Ohmoto, 1983). The deposition of galena and sphalerite before chalcopyrite and the attendant 'chalcopyrite disease' is characteristic of Kuroko ores in general (Barton, 1978) and is commonly interpreted as more intense and hotter hydrothermal activity (Eldridge *et al.*, 1983).

The chlorite alteration is characteristic of VMS alteration such as in the Pilley's Island stockwork (Tuach, 1984). Salinities of inclusion fluids are similar to those in the Kuroko stockworks (3.6-7% NaCl equivalent; Pisutha-Arnond and Ohmoto, 1983; Bryndzia *et al.*, 1983). The sulphur isotopes and high-Fe chlorites are consistent with VMS deposits, although not diagnostic.

Table 6. Geothermometry determinations from sulphur isotope pairs.

Sample	$\partial^{34}S_{py}$	$\partial^{34}S_{cp}$	$\partial^{34}S_{sp}$	Δpy-cp	T°C	Δpy-sp	T°C	Δcp-sp	T°C
CRL 1	-	3.4	-	-	-	-	-	-	-
CRL 6	5.4	2.7	2.3	2.7	138	3.0	42	0.4	na
CRL 11	5.4	2.8	-	2.6	140	-	-	-	-
CRL 12	5.0	2.3	-	2.7	133	-	-	-	-
CRL 15	6.2	-	-	-	-	-	-	-	-

Our preferred interpretation is that the Crescent Lake deposit represents alteration and mineralization in a volcanogenic hydrothermal system, possibly related to the Pilley's Island system. In the absence of detailed geochemical data from Pilley's Island, we cannot further corroborate this connection. However, geologic and whole-rock geochemical evidence suggest that the Crescent Lake deposit occurs near the base of the same calc-alkalic basalt and andesite sequence that culminates in the extrusion of a dacite dome and VMS formation in the Pilley's Island area.

CONCLUSIONS

The present study suggests that the Crescent Lake copper deposit is related to a volcanogenic hydrothermal system rather than a mesothermal auriferous hydrothermal system. The episodic fracture fillings of quartz and sulphides could represent the deeper portions of a Kuroko-type system such as Pilley's Island massive sulphides. Further documentation of the Pilley's Island isotope and mineral chemistry is needed to determine how closely Crescent Lake and Pilley's Island are related.

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