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Rb/Sr, S, and O Isotopic Analyses Indicating Source and Date of Contact Metasomatic Copper Deposits, Craigmont, British Columbia, Canada[1]

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Abstract

Rubidium-strontium dating of chalcopyrite-bearing potassium feldspar veins from the Craigmont ore body gives an initial Sr^{87}/Sr^{86} ratio of 0.7037 ± 0.0002 and an isochron of 200 ± 2 m.y., in good agreement with Northcote's 198 ± 8 m.y. K/Ar date for the presumed parent, the copper-rich Guichon batholith. The low initial Sr^{87}/Sr^{86} ratios imply that the batholithic rocks, the K feldspar gangue and associated Craigmont mineralization were derived from a mantle source similar to that of recent basalt.

Sulfur in the main ore body ranges in δ values from $+0.5‰$ to $-9.8‰$ and averages $-3.3‰$. Disseminated sulfides in the Guichon batholith have δS^{34} values close to mantle sulfur ($-0.3‰$ to $+3.0‰$) whereas disseminated sulfides in sparsely mineralized wall rocks have δS^{34} values averaging $-11.3‰$. Sulfur isotope data suggest that early in mineralization, light country rock sulfur was dominant (sulfurization) and during the late period of potash veining and chalcopyrite mineralization magmatic sulfur (meteoritic values) was emplaced. Carbon and oxygen determinations on host rock skarn and marble agree with this thesis and indicate that while little or no magmatic carbon was added to these rocks during the early period of skarn formation, late calcite associated with mineralization has δO^{18} values ranging from $-18.6‰$ to $-23.5‰$ and δC^{13} values that average $-4.2‰$, typical values for hydrothermal calcites and carbonatites, suggesting a non-limestone source for a large part of the carbonate associated with late mineralization.

Contents

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Introduction

CRAIGMONT MINE is situated in the southern part of the Highland Valley Mining District, British Columbia, (latitude 50°12'28"N, and longitude 120°-43'48"W), 240 miles northeast of Vancouver and ten miles northwest of the town of Merritt (Fig. 1). The first detailed reports on the geology and mineral deposits of the area were prepared by Cockfield (1948) and Duffell and McTaggart (1952). Carr (1960 and 1966), Rennie et al. (1961), and Bristow (1968) presented generalized reports of the geology and structure of the mine. Two recent doctoral theses (Keevil, 1965 and Drummond, 1966), give more detailed aspects of the history, geology and
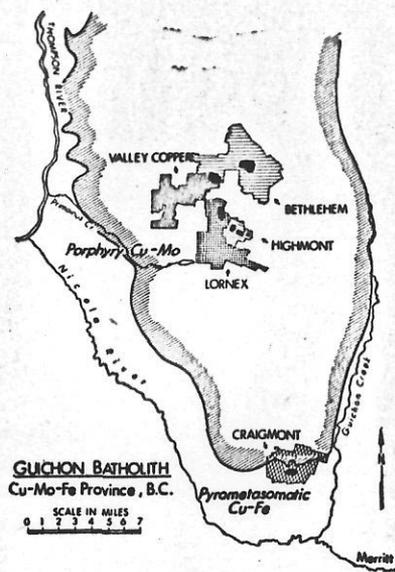
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FIG. 1. Contact Metasomatic copper-iron deposits at Craigmont, on the periphery of the Guichon batholith, in relation to the large porphyry type copper-molybdenum deposits of Highland Valley.

exploration techniques at Craigmont. Comprehensive radiometric dating studies of the Guichon Creek Batholith, which is found north of Craigmont, were presented by White et al. (1967), and Northcote (1968).

Magnetometer and soil sampling surveys provided the anomalies for diamond drilling that first encountered the Craigmont copper mineralization in 1957. Production from the Craigmont open pit began in 1961 and has averaged about 5,000 tons per day since. The Craigmont pit reached its ultimate depth in 1967 and then a highly mechanized sublevel caving method was inaugurated to recover the remaining ore. Ore produced and known reserves total about 30 million tons averaging 1.7 percent copper and 20 percent iron.

Geologic Setting

The Craigmont orebodies are located in a steeply dipping, drag-folded section of carbonate and skarn rocks within the contact aureole at the southern end of the Guichon Creek batholith. The host rocks belong to the Nicola Group of upper Triassic age and consist of siliceous hornfelsed sediments, calcium silicate skarns and marble closely associated with the ore. Chemical analyses of skarn rocks and impure limestone suggest that Si, Fe, Mg and S were added with a resultant loss of CaO and CO_2. The metasomatism seems to have taken place under conditions of hornblende-hornfels facies since grossularite-andradite garnet and diopside are present. In the large skarn zones at Craigmont the process of

metasomatism has been so intense that the original character of the calcareous rocks is no longer recognizable (Drummond, 1966).

Apophyses of Guichon batholithic rocks, mainly quartz diorites, intrude the Nicola rocks within the mine area. These Guichon rocks form the outer periphery of the batholith and change in composition toward the periphery due to assimilation of prebatholithic rocks (Northcote, 1968). On the basis of geologic evidence, the Guichon Creek batholith is older than Middle Jurassic and younger than early upper Triassic (Duffell and McTaggart, 1952). The first potassium-argon age determination of the batholith was made by Baadsgaard et al. (1961), and a date of 186 ± 5 m.y. obtained on a chloritized biotite from the Bethlehem copper property. Subsequently the Geological Survey of Canada published 11 K-Ar dates averaging 240 m.y. (Wanless et al., 1965). Northcote (1968) completed 26 K-Ar age determinations averaging 198 ± 8 m.y. for various phases of the batholith, and Dirom (1965) made 11 determinations averaging 195 m.y., in close agreement with Northcote's. The Geological Survey of Canada dates have recently been revised to new dates ranging from 184–197 m.y. (Wanless et al., 1967).

The youngest rocks at the Craigmont mine belong to the Cretaceous Kingsvale Group that unconformably overlay the Nicola rocks and the Guichon batholith. Above the Craigmont orebody, the Kingsvale volcanic rocks are unmineralized. Plant fossils found by Rice (1948) indicate that the Kingsvale rocks are late early Cretaceous (Albian) whereas a sample from near the Craigmont mine had a late Cretaceous K-Ar date of 80 m.y. (Lowdon, 1963).

Metallization

Two distinct stages of metallization occurred at Craigmont. The initial phase of disseminated magnetite, chalcopyrite and specularite formed contemporaneously with the skarn·minerals. The second phase formed when the temperature decreased, causing the rocks to become brittle and to form fractures that acted as channels and places of deposition for mineralizing fluids. This phase is characterized by irregular discontinuous veins comprised of coarse pink K-feldspar with associated chalcopyrite and specularite. The latter mineral is commonly replaced by magnetite.

Within the whole orezone, chalcopyrite is the only ore mineral and occurs widely disseminated and generally interstitial to other minerals. Small amounts of pyrite and bornite are present as disseminated crystals and there are trace amounts of earthy hematite, ilmenite, and pyrrhotite in the ore. Five major orebodies extend a total of 3,000 feet horizontally, 1,800 feet vertically and across mining

widths ranging from 10 to 350 feet (Bristow, 1968). The orebodies, controlled by the host rock structure, as a whole tend to stand vertically, however, sinuous lenses extend out from the main bodies. Considerable evidence gathered by mine geologists supports the concept of drag folding on the north limb of an east-west trending anticline.

The only feature consistently linked with the orebodies and associated metallic occurrences is the metasomatic aureole adjacent to the Guichon batholith. Within the skarn aureole, certain calc-silicates might localize the ore selectively or may just reflect contemporaneity rather than selective replacement. Fissures, the result of drag folding, were likely an important control initially whereas secondary cross faulting controls the younger mineralization. Carbonate rock and skarn at Craigmont, may act as a possible mineralization control, however, since the Number 3 orebody is not associated with carbonate or skarn rocks, such a control is not invariable.

The contemporaneity of the emplacement of the Guichon batholith and ore mineralization, the ore mineralogy, abundance of skarn and proximity of ore to igneous contacts at the Craigmont deposit place this important orebody into the pyrometasomatic class of ore deposits as defined by Lindgren (1933) and elaborated by Bateman (1950).

Isotope Studies

Rubidium-Strontium

Radiometric dating was used in an attempt to determine the age and genesis of the Craigmont mineralization and the relationship of the Guichon batholith to the orebodies. Six whole rock samples were dated by the rubidium-strontium isochron method. Four samples of potassium feldspar rich rock from the orezone and two quartz monzonites from the northern part of the Guichon batholith were used. The K-feldspar rich ore is contemporaneous with the second or veining phase of mineralization and is associated with specularite and chalcopyrite. Sample descriptions and locations are outlined in the Appendix.

For this study the Rb^{87} decay constant used was 1.39×10^{-11} years^{-1} (50 b.y. half-life). A six inch, 60 degree deflection solid source mass spectrometer with a single filament source and a single collector cup was used to measure the rubidium and strontium isotope ratios. For each sample an aliquot was taken to which a strontium tracer or spike was added. Both the spiked and unspiked portions of each sample were analyzed. Data on sample preparation and analytical procedures used for this study are given by De la Cruz (1967).

TABLE 1

RUBIDIUM - STRONTIUM ANALYTICAL DATA FOR WHOLE ROCK ISOCHRON

$(Sr^{87}/Sr^{86})_0 = 0.7037 \pm .0002$ $t = 200 \pm 2$ m.y.

Sample number	Specimen type	Rb^{87} (p.p.m.)	Common Sr (p.p.m.)	$\frac{Sr^{87}Rad}{Sr^{87}N}$	$\frac{87Rb}{86Sr}$	$\frac{87Sr}{86Sr}$ (atomic ratios)		
						Spiked	Unspiked	Mean
6243	K-feldspar	38.7	93.8	0.016	4.217	0.7161	0.7154	0.7157
6250	K-feldspar	82.3	37.7	0.087	22.297	0.7661	0.7652	0.7656
6259	K-feldspar	18.6	76.2	0.010	2.493	0.7106	0.7110	0.7108
6271 (AK-209)	K-feldspar	87.3	94.0	0.037	9.480	0.7303	f	0.7303
66-58A	Quartz monzonite	31.1	131.6	0.010	2.412	0.7083*	0.7109	0.7096
4011A-I	Quartz monzonite	27.2	199.0	0.004	1.394	0.7088	0.7070	0.7079

f failed run
* Sr^{84} spike for this run only

Results.—The six analyzed samples form an isochron, which gives a date of 200 ± 2 million years and an initial Sr^{87}/Sr^{86} ratio of 0.7037 ± 0.0002. The analytical data are shown in Table 1, and the isochron plot in Figure 2. The samples show excellent colinearity. This small deviation of linearity of the isochron falls well within usual analytical error limits. Replicate analyses at the University of Alberta geochronology laboratory yield variance estimates for Sr^{87}/Sr^{86} and Rb^{87}/Sr^{86} such that the error could be about ±5 m.y. and still fall within general error limits.

The date of 200 ± 2 m.y. agrees closely with potassium argon dating of the Guichon Batholith by workers from University of British Columbia and the recent dates by the Geological Survey of Canada. This agreement and the colinearity of samples lead the writers to postulate that intrusion (cooling) and mineralization were essentially contemporaneous and that a genetic relationship between the Craigmont mineralization and the Guichon batholith exists.

The initial Sr^{87}/Sr^{86} ratio from the isochron plot may be used to indicate the source of the Craigmont mineralization. The general principles of this approach were outlined by Faure and Hurley (1963)
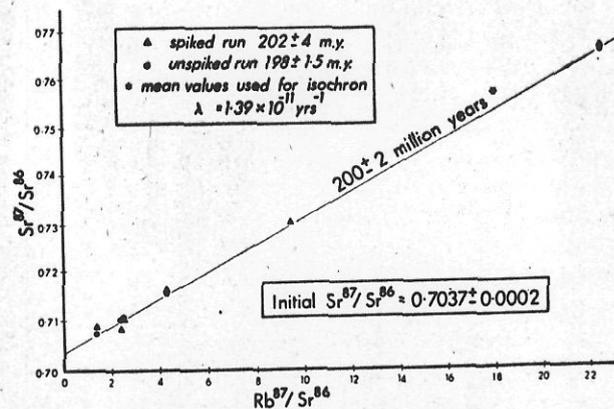

Fig. 2. 200 m.y. rubidium-strontium isochron for Craigmont mineralization and Guichon batholith rocks.

and have been applied to ore deposits by Moorbath et al. (1967). A meaningful interpretation of the genesis must consider whether the batholith and ores were derived by melting at depth of relatively copper- and iron-rich crustal metamorphic rocks or by differentiation from magmas derived from primary material below the crust, and also whether or not lateral secretion from the intruded Nicola rocks played a part in mineralization (Ney 1966). If the Guichon batholithic rocks and gangue minerals associated with the mineralization were derived in part from older crustal rocks, then the initial Sr^{87}/Sr^{86} ratios should fall in the range 0.706 to 0.708 or higher (Peterman et al., 1967). The initial Sr^{87}/Sr^{86} ratio for the Craigmont isochron is 0.7037 which falls into the range of values (0.703–0.706) of recent basalts (Hedge, 1966). It is therefore concluded that the ore minerals and K-feldspar gangue did not originate by fusion of ancient sialic basement or Cache Creek or Nicola rocks, but must have developed in an environment with low Sr^{87}/Sr^{86} ratios.

TABLE 2

SAMPLE DESCRIPTIONS AND ANALYTICAL DATA FOR SULFUR ISOTOPES

Sample	Description	Mineral	δS^{34}‰.*
66-58A:	Quartz monzonite, Guichon Batholith; 121° 13'W, 50° 34' N; diss pyrite.	py	+3.0
4011A:	Quartz monzonite, Guichon Batholith; 120° 51'W, 50° 29'30"N; diss pyrite.	py	+1.9
6246A:	Hornblende diorite, underground; 10, 315N, 9570E, 3666' elev; diss pyrite.	py	+0.2
6246B:	Quartz–sericite veinlet cutting 6246A; 10, 315N, 9570E, 3666' elev; diss pyrite.	py	-0.3
6248:	Greywacke wall rock; open pit; 10, 010N, 8400E, 3534' elev; finely diss pyrite.	py	-7.6
6273:	Marble wall rock; 10, 390N, 7470E, 3065' elev; finely diss chalcopyrite.	chpy	-15.0
6243:	K-feldspar gangue; 10, 300N, 9370E, 3600' elev; massive diss blebs of chalcopyrite.	chpy	+0.5
6244:	Garnet epidote skarn orebody; 10, 330N, 9410E, 3666' elev; finely diss chalcopyrite.	chpy	-0.2
6245:	Massive magnetite; 10, 330N, 9400E, 3666' elev; finely diss chalcopyrite.	chpy	-2.0
6249:	Massive specularite; 10, 150N, 8370E, 3534' elev; fine-grained chalcopyrite.	chpy	-3.4
6264:	Massive chalcopyrite; 2852' elev. 821 X-cut from high grade section of orebody.	chpy	-9.8
6265:	Massive platy magnetite; 2852' elev. 821 X-cut north; diss chalcopyrite.	chpy	-5.0
6285:	Limestone country rock; 10, 264N, 6851E, 3072' elev; finely diss pyrite.	py	-33.0
66-60:	Quartz diorite; chalcopyrite impregnation along minute fissure; 120° 11'W, 50° 40'N.	chpy	-2.0
55099	Mill concentrates,Bethlehem Copper,Ashcroft,B.C. Sampled May 19, 1967		-3.6
V68-1294	Sampled April 19-20, 1968		-3.6

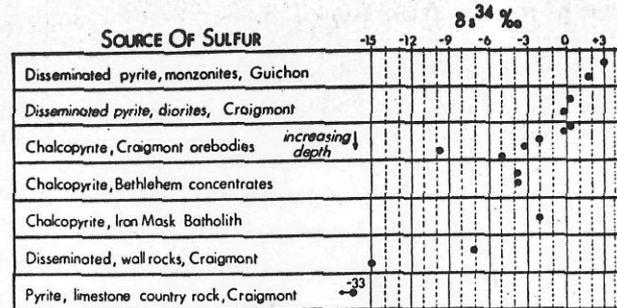* Standard deviation based on reproducibility = + 0.2 permil.

FIG. 3. Sulfur in the Craigmont ore bodies appears to be of mixed origin, some having an isotopic composition similar to the sulfur of the Guichon batholith, some an isotopic composition similar to that of sulfur in the wall rocks.

similar to recent basalt. Such a source could be either reabsorbed oceanic crust (Wilson 1968), the upper mantle, or a basic layer in the lower part of the crust or possibly Nicola or Cache Creek volcanic rocks. However, the Nicola and Cache Creek rocks do not contain extensive basic volcanic layers in the Craigmont area.

Sulfur Isotopes

Stable sulfur isotope variations in Craigmont sulfide minerals were studied to help interpret mineral genesis. Six pyrite and eight chalcopyrite mineral separates were analyzed for their S^{34}/S^{32} ratios. The various sample associations, descriptions and locations are outlined in Table 2. A 12 inch, 90 degree magnetic analyzer mass spectrometer equipped for simultaneous collection of masses 66 and 64 was used to measure sulfur isotope ratios. Procedures of sample preparation and mass spectrometric analysis used for the study are similar to those given by Ryznar et al. (1967). The results are expressed as δS^{34} permil deviations with respect to the troilite sulfur of the Cañon Diablo meteorite.

The routine analyses were compared with two working standards: one is a pyrite from Quemont, Quebec ($\delta S^{34} = +1.1$ permil) and the other is a seawater sulfate from the Pacific Ocean ($\delta S^{34} = +20.2$ permil). The calculated analytical precision of the present study based on reproducibility expressed as standard deviation was ± 0.2 permil.

Results.—The variance in results is graphically illustrated in Figure 3, with the samples grouped into five geologically distinct associations. Two pyrite samples from Guichon batholith rocks, believed to be primary sulfides formed contemporaneously with the enclosed batholith, have δS^{34} values of +1.9 and +3.0 permil. These ratios are in the range normally noted for igneous sulfur of possible upper mantle origin (Ault and Kulp, 1959; Thode, 1963). Disseminated pyrite samples from intrusive

diorites, collected underground at Craigmont, have similar mantle type values (+0.2 and −0.3 permil).

In contrast two samples from sparsely mineralized wallrocks, a disseminated pyrite from graywacke, and a finely disseminated chalcopyrite in a recrystallized limestone, have δS^{34} values of −7.6 and −15.0 permil, respectively. These values, moderately enriched in S^{32}, are characteristic of sedimentary sulfides (Thode et al., 1949; Ault and Kulp, 1959). Sample #6285 may be considered representative of the country rock in the Craigmont area and its sulfur is highly enriched in S^{32} (δS^{34}‰−33.0).

Six samples of chalcopyrite from the main orebodies have δS^{34} values ranging from +0.5 to −9.8 permil. Except for two specimens having δS^{34} values of −9.8 and −5.0 permil, the data are relatively close to the value for meteoritic or mantle sulfur (near zero permil). Significantly, almost all Cordilleran hydrothermal orebodies of magmatic association exhibit δS^{34} values near zero permil (Jensen, 1967).

Mill concentrates from the one operating mine in the Highland Valley area, Bethlehem, give very consistent δS^{34} values of −3.6‰ negative, but close to meteoritic values, and quite similar to most Craigmont values.

The δS^{34} values of −9.8 permil for sample #6264 and −5.0 permil for sample #6265 are rather unusual for products of primary igneous processes. Similarity between this value and those obtained from the wall rock sulfides indicates that they have a common source of sulfur. If part of the sulfur in the orebodies was derived from the country rock this would explain the slight enrichment in S^{32} in most Craigmont ore samples compared to the sulfur in the primary igneous sulfides from the Guichon Batholith. The origin of massive sulfide deposits by introduction of country rock sulfur (sulfurization) has been summarized by Cheney and Lange (1967). Sulfurization processes at Craigmont may have been activated by high temperatures contributing to recrystallization of limestone, rock fracturing and skarn formation.

Data tentatively suggest two possible sources for the sulfur of this deposit—deep magmatic and adjacent country rocks. Evidence based on a limited number of samples indicates that sulfurization may have occurred only during the period of initial skarn formation and not during the second phase or veining phase of mineralization. For example chalcopyrite from sample #6243 gives a δS^{34} value of +0.5 permil, close to meteoritic. This sample, representative of the second stage of mineralization carrying abundant K-feldspar gangue, appears to be of deep-seated origin in that it contains mantle type sulfur associated with feldspar of an initial Sr^{87}/Sr^{86} (0.7037) of mantle values.

The fairly wide range of δS^{34} values observed in samples from the main orebodies could result from the mixing of magmatic sulfur and country rock sulfur in various proportions. The possibility remains that sulfur isotope fractionation may have resulted from the sulfur-bearing minerals crystallizing directly from primary hydrothermal solutions without any introduction of country rock sulfur. However, isotopic behavior during ore-forming processes is not well understood and to date no conclusive evidence has been presented that fractionation equivalent to that found in Craigmont's main orebodies could result from direct crystallization. The possible depth effect is intriguing; the S^{34} enrichment is in the opposite direction to that noted by Ryznar et al. (1967), at Quemont, but further speculation is difficult because of a limited number of data.

Oxygen and Carbon Isotopes

Stable carbon and oxygen isotope ratios from Craigmont marbles and hydrothermal calcites help elucidate the process of skarn formation and arrive at the genesis of late calcite, which is in part associated with the ore minerals. Thirty-one samples analyzed for their carbon and oxygen ratios are tabulated in Table 3 and graphically illustrated in Figure 4.

The carbonate samples were reacted with 100% phosphoric acid (McCrea, 1950) and the carbon dioxide obtained analyzed in a 12 inch 90° mass spectrometer using a double collecting system. The data are reported as permil deviation relative to the PDB Chicago belemnite Standard (δ denomination).
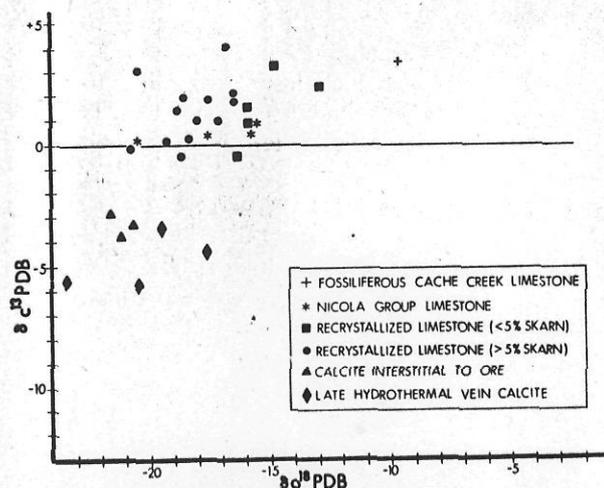

FIG. 4. Recrystallized marine limestones (marbles) and skarns have an oxygen and carbon isotopic composition distinctly different from that of late calcites associated with copper ore at Craigmont.

TABLE 3 THE OXYGEN AND CARBON ISOTOPIC COMPOSITION OF CARBONATES FROM CRAIGMONT, B.C.

SAMPLE NO.	ROCK TYPE	COMMENTS	δO^{18} ‰	δC^{13} ‰
LIMESTONES FROM NICOLA AND CACHE CREEK GROUPS				
6279	Ls	Impure black limestone, minor amounts of dolomite, Nicola Group	-20.4	+0.1
C54	Ls	Dark fossiliferous limestone, Nicola Group, about 1 mile from nearest intrusive	-14.6	+0.9
C56	Ls	idem	-17.4	+0.3
C57	Ls	idem	-14.4	+0.5
6274	Ls	Limestone from Cache Creek Group (Permian) west of Kamloops, B.C.	-9.6	+3.3
METAMORPHOSED LIMESTONE WITH LESS THAN 5% SKARN MINERALS				
6272	Marble	Pure marble, trace amounts of skarn minerals	-16.3	-0.6
6281	Marble	About 3% skarn minerals present	-15.9	+1.5
6283	Marble	Less than 3% skarn minerals present	-15.7	+0.8
6292	Marble	Partly recrystallized limestone	-12.8	+2.3
		About 4% skarn minerals present		+3.1
METAMORPHOSED LIMESTONES WITH MORE THAN 5% SKARN MINERALS				
6255A	Marble	From main ore zone, contains a variety of skarn minerals	-18.0	+1.0
6273	Marble	Within 5 feet of known ore	-18.8	+1.4
7276	Marble	From ore zone, this banded marble is highly altered with considerable quartz grains	-17.1	+0.9
6280	Marble	Not a typical recrystallized limestone, contains fine grained calcite and rounded quartz grains	-17.5	+1.8
6284	Marble	Slightly altered, contains numerous feldspar grains. Collected about 300 feet from mineralization	-18.6	-0.5
6285	Marble	About 100 feet from mineralization, iron stain around calcite crystals	-16.4	+1.7
6286A	Marble	Breccia fragments containing twinned calcite, diopside and quartz	-16.4	+2.1
6286B	Calcite	Calcite cement between breccia fragments of sample 6286A	-18.5	+0.2
6287	Marble	Sample taken within 5 feet of mineralization. Contains abundant skarn minerals, fine grained texture	-18.5	+1.9
6288	Marble	Collected 60 feet from known mineralization	-16.7	+4.0
6290	Marble	This altered marble contains about 20% skarn minerals and was collected adjacent to mineralization	-20.4	+3.0
6291	Marble	Medium grained calcite with minor amounts of skarn minerals. Collected 10 feet from massive mineralization	-20.7	-0.2
6293	Marble	Calcite with 20% skarn minerals, 200 feet from ore	-19.2	+0.1
HYDROTHERMAL CALCITES				
6258	Calcite	Calcite interstitial to chalcopyrite and quartz, from main ore zone.	-20.6	-3.3
6264	Calcite	Calcite interstitial to massive chalcopyrite, from main ore zone	-21.2	-3.8
6255	Calcite	White coarse euhedral crystals of calcite from main orezone	-21.5	-2.9
6275	Calcite	White fine grained massive calcite	-18.6	-4.4
6277	Calcite	Fine grained white calcite veinlet	-20.5	-5.8
6278	Calcite	Fine grained white calcite veinlet	-19.4	-3.5
6284	Calcite	Narrow calcite veinlet	-23.5	-5.6
6295	Calcite	Weathered vuggy calcite veinlet	-22.7	-12.8

Entry 6294 immediately following 6292 is incomplete. Add Rock Type = Marble; δO^{18} °/oo = -14.7.

Appropriate corrections described by Craig (1957) were applied. The overall reproducibility is better than ±0.2 permil for oxygen and carbon.

Results.—The least altered limestones found near the Craigmont mining district are the dark limestones from the Nicola and Cache Creek Groups. Their δO^{18} values (ranging from -9.6 to -20.4 permil) are not representative for Triassic or Paleozoic marine limestones, which have, according to Keith and Weber (1964), a higher O^{18} content. The δC^{13} values of these limestones fall in the range from +3.3 to +0.1 permil.

Recrystallized limestones or marbles that are host rocks for the Craigmont mineralization comprise the largest group of analyzed samples. These marbles have been divided into two groups according to the percentage, estimated from stained thin sections, of skarn minerals present. The δO^{18} values of marble samples range from -16.4 to -20.7 permil and the δC^{13} values range from +4.0 to -0.5 permil. Marbles with less than 5 per cent skarn minerals, have δO^{18} values ranging from -12.8 to -16.3 permil which are slightly more enriched in O^{18} than samples containing more skarn minerals. The δC^{13} values range from +3.1 to -0.6 permil between the two marble groups. Two samples (#6273 and #6287) collected within five feet of known mineralization, do not differ isotopically from samples collected several hundred feet from mineralization.

White coarsely crystalline late calcite that is associated with the second phase of mineralization and with massive chalcopyrite from the main orezones is isotopically distinct as shown in Figure 4. For this group of samples the δO^{18} values range from -18.6 to -23.5 permil and the δC^{13} values range from -2.9 to -12.8 permil. These values indicate enrichment in the lighter isotopes for both oxygen and carbon. Sample #6295 which has a δC^{13} value of -12.8 permil is anomalous and in hand specimen shows the effects of recent weathering. Three samples (#6258, #6264 and #6255) of calcites that were interstitial to ore minerals from the main orezone have an average δC^{13} value of -3.3 permil.

Discussion of Results.—During contact metamorphism, Nicola rocks were recrystallized and disseminated skarn minerals formed along with chalcopyrite, magnetite, and specularite. Elevated temperatures during this process and decreasing oxygen isotope fractionation between water and the carbonate in the Craigmont limestones resulted in lighter δO^{18} values in the analyzed marbles compared to the original marine limestones. It was found that

analyzed specimens with higher skarn content tend to have lower δO^{18} values in agreement with their more pronounced higher temperature metamorphism. In contrast the δC^{13} values of the marbles became isotopically lighter by about only 1 or 2 permil. This small change in δC^{13} values indicates that most of the CO_2 present, was generated in situ.

The δO^{18} and δC^{13} values distinguish the late calcite from the marble groups as indicated in Table 3. Significantly, the δC^{13} values for the late calcite are about 5–6 permil lighter than the marble group, whereas those for oxygen seem to have a tendency toward slightly lighter values. The average δC^{13} for the late calcite, excluding sample #6295 which is weathered, is −4.2 permil.

Using this value as reference, the carbon isotopic composition of the carbon involved in the formation of this young calcite is estimated to be about −4 to −6 permil. These values fall in the upper range recorded for carbonates believed to be precipitated under the influence of magmatic carbon dioxide. Rye (1966) estimated that the δC^{13} values were −7 to −9 permil for carbon deposited by hydrothermal ore fluids derived from a magmatic source or cooling intrusion. The δC^{13} values of carbonatite ejecta in Pleistocene tuffs from Germany, believed to represent primary igneous carbon derived from a gabbroic magma, give a range of −6.6 to −8.4 permil (Taylor et al., 1965). The similarity between these values and those obtained for Craigmont substantiates a non-limestone source for a large portion of carbon in late calcite veinlets and for calcite interstitial to ore minerals.

The carbon and oxygen data also possibly support the hypothesis that during the initial phase of mineralization (skarn formation), the orebodies may have formed partially by sulfurization. The similarity of the δC^{13} values from marbles adjacent to the main orebodies and those from unaltered country rock limestone lends support to partial origin by sulfurization. During the second phase of mineralization, the carbon data of the late calcites infers that carbon in the form of CO_2 ascended from the mantle or a deep-seated source in contrast to small amounts, if any, during the earlier skarn formation.

Conclusions

During late Triassic and early Jurassic times, an extensive metallogenic epoch occurred in British Columbia. Mineral deposits indicated to have formed during this epoch on the basis of K-Ar dating are Bethlehem and the other Guichon Cu-Mo deposits, Copper Mountain, and Stikine Copper, forming a belt shaped western Cu-Mo metallographic province (White et al., 1967; Sinclair and White, 1968; and White and Carter, 1968). Craigmont can now be added to the list. At each of these mineral properties related intrusive rocks, radiometrically the same age as the mineralization, indicate a genetic association between Triassic-Jurassic plutonism and mineralization.

At Craigmont sulfur isotopes suggest that sulfides in the batholith and orebodies are related. The orebodies are slightly enriched in S^{32} by a limited wall rock contribution through sulfurization. A deep seated source is substantiated by the low initial Sr^{87}/Sr^{86} ratio from K-feldspar gangue and by the low δC^{13} carbon isotope values for calcite associated with the ore. The principal host rocks (other than granitic rocks) for the majority of the copper deposits in western British Columbia are upper Triassic and Jurassic volcanic rocks. These rocks are notably rich in trace amounts of copper (about 100 ppm) and this observation has led many workers such as Ney (1966) and Baragar, Goodwin and Souther (1966) to suggest that these rocks were the major copper source. Volcanic rocks in the Nicola Group are not abundant at Craigmont, but, interestingly, the sulfur isotope data suggest that at least some of the sulfur is from the country rocks.

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Appendix A

Specimens from Craigmont Mine, B.C.

Note: Number in ( ) refers to those labelled on specimens. Mine coordinates are used.

M6243	(C-1)	Feldspathic gangue, 10300N, 9370E, 3,600 elev.
6244	(C-2)	Chlorite, epidote, garnet skarn; 10330N, 9410E, 3,666 elev.
6245	(C-3)	Massive magnetite, 10330N, 9400E, 3,666 elev.
6246	(C-4)	Diorite, 10315N, 9570E, 3,666 elev.
6247	(C-5)	Andesite hornfels, 9985N, 8560E, 3534 elev.
6248	(C-6)	Argillite hornfels, 10010N, 8400E, 3,564 elev.
6249	(C-7)	Skarn with specularite and chalcopyrite, 10150N, 8370E, 3,534 elev.
6250	(C-8)	Feldspathic gangue, 10140N, 8320E, 3,534 elev.
6251	(C-9)	Chlorite hornfels, 10210N, 8480E, 3,468 elev.
6252	(C-10)	Andesite (Kingsvale Group), 9480N, 8130E, 4,062 elev.
6253	(C-11)	Hornblende basalt (Kingsvale Group), 9480N, 8130E, 4,062 elev.
6254	(C-12)	Diorite, 3,060 elev. at shaft #2.
6255	(C-13)	Marble with minor skarn minerals, 3,060 elev. at shaft #2.
6256	(C-14)	Actinolite, epidote, chlorite skarn, 30-783 Service drift east.
6257	(C-15)	Massive specularite, 30-783 Service drift east.
6258	(C-16)	Chalcopyrite and skarn minerals, 30-783 Service drift east.

6259 (C-17) Feldspathic gangue, 3,590 elev. at 771 Ore pass.

6260 (C-18) Diorite? highly altered, 3,590 elev. at foot of 3,620

6261 (C-19) Massive magnetite and specularite, 3,464 elev. in Haulage drift #1.

6262 (C-20) Hornfelsed quartzofeldspathic sandstone; 3,465–3,537 Ramp, south of Shaft #1.

6263 (C-21) Hornfels wacke, 34-751 Access drift.

6264 (C-22) Chalcopyrite, quartz skarn and calcite, 2,852 elev. 821 Crosscut north.

6265 (C-23) Magnetite skarn, 2,852 elev. 821 Crosscut north.

6266 (C-24) Hornblende diorite, 2,852 elev. at shaft #2.

6267 (C-25) Hornblende diorite, 2,852 elev. at shaft #2.

6268 (C-26) Andesite; On Spences Bridge road 7/10 of a mile west of the Craigmont road turnoff.

6269 (C-27) Volcanic breccia from Diamond drill hole #S-61.

6270 (C-28) Porphyritic andesite; from Craigmont surface diamond drilling.

6271 (C-29) Massive magnetite with K-spar, from 3,500 elev. Specimen was collected by Rennie in 1961 and a K-Ar age determination was made on it. (AK-209).

6272 (C-30) Pure marble, 10430, 7400E, 3,070 elev.

6273 (C-31) Marble with some skarn minerals, 10390N, 7470E, 3,065 elev.

6274 (C-32) Powdered limestone taken from outside the brachial valve of a *Linoproductus cora (d'Orb)*, Permian, from the fossil collection of P. S. Warren at the Univ. of Alberta.

6275 (C-33) 10625N, 6385E, 3,533 elev. Recrystallized limestone.

6276 (C-34) Limestone, 10080N, 7550E, 3,560 elev.

6277 (C-35) Calcite veinlet, 10175N, 8720E, 3,390 elev.

6279 (C-37) Impure black limestone, 9300N, 700E, 5,165 elev.

6280 (C-38) Recrystallized limestone, 7500N, 2400E, 5,265 elev.

6281 (C-39) Limestone skarn, 10970N, 2540E, 4,550 elev.

6282 (C-40) Young calcite veinlet, hydrothermal, 11520N, 2440E, 2,630 elev.

6283 (C-41) Partly recrystallized limestone, 9200N, 210E, 4,525 elev.

6284 (C-42) Limestone skarn, 10168N, 6865E, 3,068 elev.

6285 (C-43) Limestone skarn, 10224N, 6857E, 3,070 elev.

6286 (C-44) Limestone breccia cemented with a remobilized calcite, 10264N, 6851E, **3,072 elev.**

6287 (C-45) Limestone skarn, 10317N, 6843E, 3,074 elev.

6288 (C-46) Limestone skarn, 10215N, 7460E, 3,015 elev.

6289 (C-47) Limestone skarn, 10270N, 7452E, 2,985 elev.

6290 (C-48) Limestone skarn, 10300N, 7447E, 2,965 elev.

6291 (C-49) Limestone skarn, 10325N, 7444E, 2,950 elev.

6292 (C-50) Relatively unaltered limestone, 10355N, 7440E, 2,935 elev.

6293 (C-53) Limestone skarn, 10105N, 7478E, 3,082 elev.

6294 (C-52) Relatively unaltered limestone, 9785N, 7535E, 3,347 elev.

6295 (C-53) Calcite veinlet, 10515N, 7406E, 3,674 elev.

Petrographic Descriptions and Locations of Samples Used for Rb-Sr Dating

6243 Potassium feldspar gangue
Location: 10,300N; 9370E; 3600′ elev.—open pit
Description: The specimen is coarse-grained, pink colour and holocrystalline. Perthite (K-feldspar with intergrown plagioclase) is present with minor amounts of coarse microcline and plagioclase. The feldspars which comprise 85–90% of the specimen are cloudy and often iron stained. Fine-grained quartz is found interstitial to the feldspar. Minor disseminations of chalcopyrite and specularite with trace amounts of calcite, chlorite, epidote, sphene and actinolite comprise the other minerals.

6250 Potassium feldspar gangue
Location: 10,140N; 8320E; 3534′ elev.—open pit
Description: The specimen is coarse-grained, buff to pink in colour, holocrystalline and comprised of inequigranular crystals, predominantly cloudy grains of K-feldspar with minor amounts of perthite and microcline. Together the feldspars comprise about 90% of the specimen. Vermicular textured intergrown quartz and K-feldspar is present in small amounts. Individual quartz grains comprise about 8% of specimen. Trace amounts of epidote, chlorite, chalcopyrite and specularite are present.

6259 Potassium feldspar gangue
Location: 3590′ elev. at 771 Ore Pass—underground
Description: The specimen is fine to medium-grained, reddish buff coloured and holocrystalline. K-feldspar 45% of total with 25% of quartz are intergrown forming a graphic texture. Some coarse grains of untwinned feldspar and quartz in about equal amounts form the remainder of specimen. Trace amounts of epi-

dote, chlorite and apatite are present. Specimen is from a vein about two feet thick.

6271   Potassium feldspar gangue
(AK209) Location: 3500 Level near entrance—underground
          Description: Specimen is medium to coarse-grained consisting of pink fragments (breccia) of cloudy feldspar with massive interstitial euhedral magnetite. The cloudy K-feldspar which comprises about 50% of specimen contains disseminated euhedral crystals of magnetite and actinolite with minor amounts of sericite. Other minerals and their approximate abundance are: magnetite—20%, quartz—10%, calcite—10% and trace amounts of chlorite, epidote and chalcopyrite.

66-58A   Quartz monzonite variety of Guichon Batholith
          Location: 121°13′W; 50°34′N; On Highland Valley road 13.1 miles south of town of Ashcroft

Description: Specimen is medium-grained holocrystalline and the crystals are inequigranular and hypidiomorphic. It is comprised of 40% quartz, 20% K-feldspar and 30% plagioclase (Oligoclase). The K-feldspar is cloudy compared to plagioclase and usually is sericitized. A few grains of perthite are also present. Biotite 2–5%, and trace amounts of chlorite, sphene, epidote, magnetite and sericite make up the remainder of the minerals.

4011A   Quartz monzonite-granodiorite variety of Guichon Batholith
          Location: 120°52′W; 50°29′30″N
          Description: This medium-grained holocrystalline specimen is comprised of about 60% quartz, 20% highly sericitized cloudy K-feldspar and 20% sodic plagioclase that is relatively unaltered and often shows albite twinning. Biotite averages about 5%. The remainder is made up of trace amounts of magnetite and epidote, the latter occurring as small veinlets.