Sulphur Sources for Gold Deposits in the Bridge River–Bralorne Mineral District, Southwestern British Columbia (Part of NTS 092J)

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Introduction

The Bridge River–Bralorne mineral district is the largest historical lode-Au producer in British Columbia, collectively producing over 4 million oz of Au between 1897 and 1971 (Church, 1996). The district covers an area of approximately 1700 km^2 and is located 180 km north of Vancouver, on the eastern side of the Coast Belt, in southwestern BC (Figure 1).

Although dominated by Au occurrences, the camp is characterized by three main metal associations: Au dominant, Sb dominant and Hg dominant. The numerous deposits and mineral occurrences that make up this district form a spatial zonation, with Au in the west, Sb in the centre and Hg in the east (Pearson, 1975). There is no definitive explanation for this distribution, but a number of geological models have been suggested. Leitch et al. (1991a) conducted a detailed geochronological analysis on the Bralorne Au deposits, and concluded that the source of the fluids was from the intrusive rocks that form the Coast Plutonic Complex to the west, and as they cooled, they sent out pulses of heat and fluid toward the east, resulting in the current metal zonation. After this analysis, Leitch et al. (1991b) performed a geochemical and isotopic analysis on the Au deposits from the Bralorne-Pioneer camp and construed that the fluids actually had a mix of metamorphic and magmatic origins, with an increase in mixing with meteoric fluids as the depth decreased. Church (1996) concluded that the close proximity of the Bendor batholith and Coast Plutonic Complex provided the structural controls and heat source for the circulation of connate and young fluids that formed the orogenic Au deposits at Bridge River–Bralorne
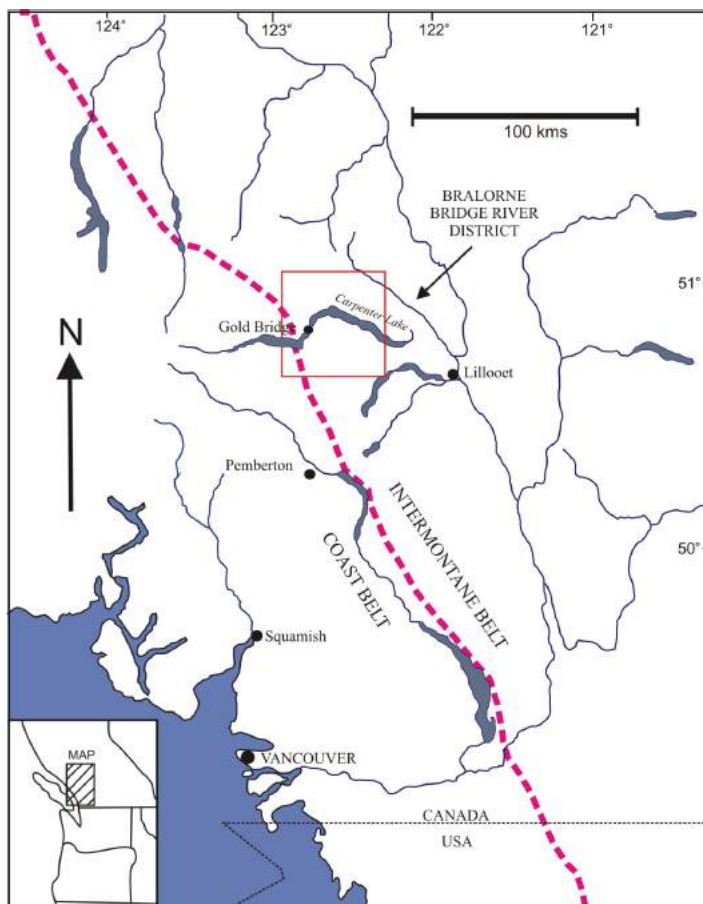

Figure 1. Location of the Bridge River–Bralorne mineral district in BC. The pink dotted line represents the boundary between the Coast Belt and the Intermontane Belt.

mineral district. However, Ash (2001) suggested an ophiolitic association for the Au deposits, and that mineralization occurred during their obduction in the mid-Cretaceous. Maheux (1989) conducted a stable-isotope and fluid-inclusion study on the larger Sb deposits and on the basis of the data, deduced that a meteoric-derived hydrothermal fluid was the source for the district metal zonation. Schiarizza et al. (1997), on the basis of regional mapping, decided that episodic reactivation of strike-slip faults gave rise to metallogenic events that resulted in the metal
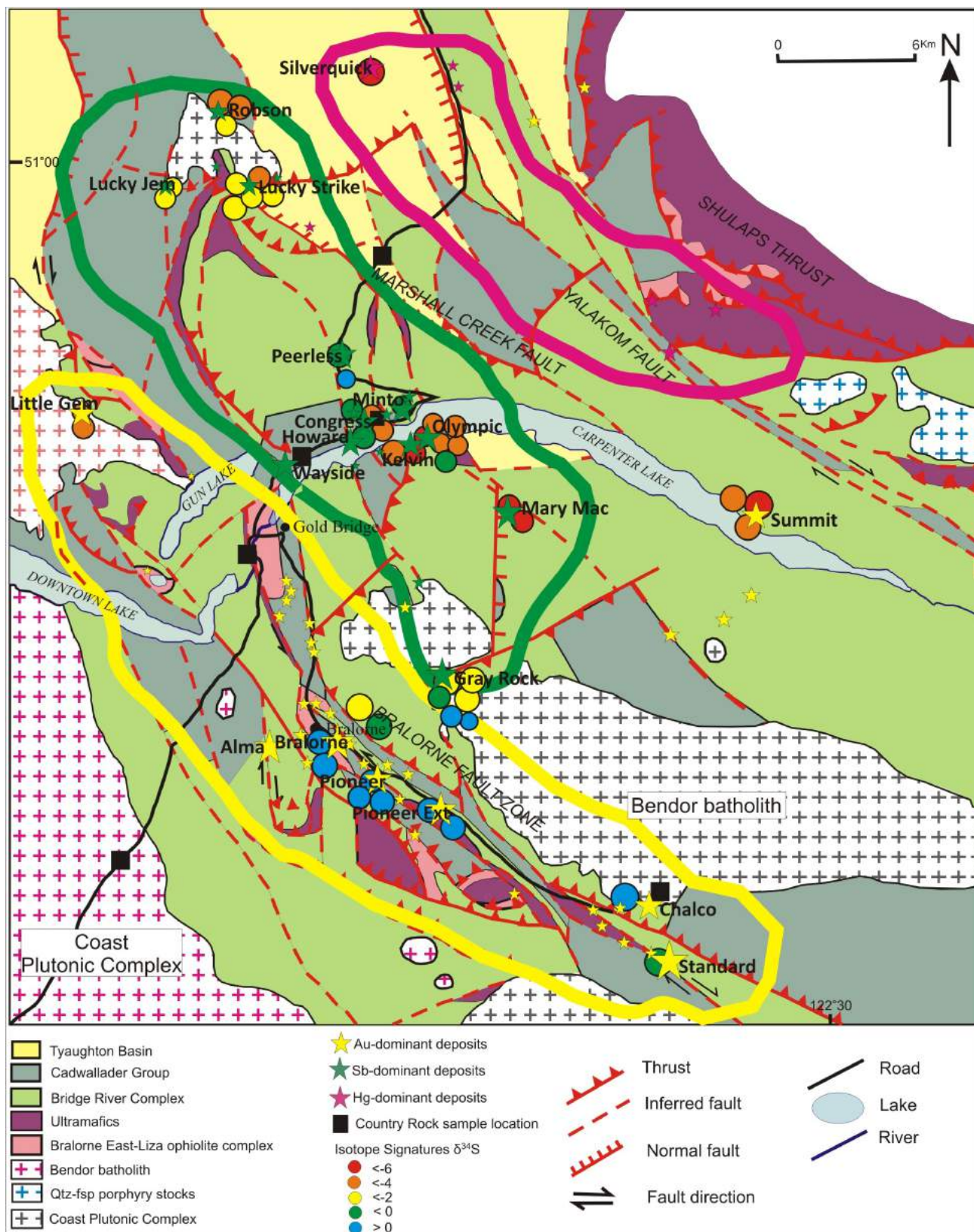
Figure 2. Regional geology of the Bridge River–Bralorne mineral district, showing deposit type and distribution. Distribution pattern is represented by circular coloured lines; green, Sb type; pink, Hg type; yellow, Au type. Larger stars are sampled deposits and occurrences. *Modified after* Church (1996), Maheux (1989) and Schiarizza et al. (1997).

zonation in the district. Specifically, the three main faults (Bralorne-Eldorado, Castle Pass, Marshall Creek–Yalakom) were active at different times, producing three mineralizing events. Determining the correct source for the S and fluids is important because it can be used to generate more effective exploration models.

Various isotopic methods can be applied to hydrothermal deposits to provide constraints on their formation models. Sulphur isotopes, in particular, can be a powerful tool to identify the source(s) of S in hydrothermal mineral systems. Although the Bridge River–Bralorne mineral district benefits from a significant amount of geochemical data (Leitch et al., 1989, 1991b; Maheux, 1989), the S source(s) responsible for the mineralization, and likely for Au transport, have not been identified. Therefore, verifying the S isotopic compositions of the mineralization and potential source rocks can assist in eliminating some confusion and will help define an exploration model and provide a strong foundation to evaluate the overall Au prospectivity of the district.

A detailed S isotope study was conducted, with samples taken from all three metal zones, as well as from the numerous rock units that form the country rocks and are considered to be potential S sources.

Regional Geology

The Bridge River–Bralorne mineral district straddles the boundary between the Middle Jurassic–Late Cretaceous Coast Belt and the Late Paleozoic–Mesozoic Intermontane Belt that together comprise this part of the southwestern Canadian Cordillera (Schiarizza et al., 1997). This complex region resulted from episodic deformational, depositional and magmatic events from the Late Paleozoic to Middle Tertiary. In the Middle–Late Jurassic, two main tectonic assemblages collided: the oceanic backarc basin Bridge River Complex (Figure 2) comprising basalt, gabbro, chert, shale, argillite and ultramafic rocks was juxtaposed with the island arc Cadwallader Group, which consists of volcanic rocks and marine and arc-marginal clastic strata (Schiarizza et al., 1997). During and after terrane collision, the Late Jurassic–Cretaceous Tyaughton Basin, which consists of mostly clastic sedimentary rocks and shale, was deposited on top of these two terranes (Church, 1996).

Contractional deformation during the mid-Cretaceous resulted in a series of major structural systems. In the Bridge River district, these are the Bralorne fault zone (Cadwallader break), the Yalakom fault system, the Shulaps thrust and a network of northwest-trending faults (Figure 2; Leitch, 1990; Schiarizza et al., 1997). Deformation above the Cadwallader Group occurred along the Shulaps thrust, the Bralorne fault zone and Bralorne–East Liza ophiolite assemblages, respectively, resulting in wedges of ophiolite and ultramafic rocks along these zones,

marking the region of crustal shortening. The ophiolite rocks include greenstone, diorite, gabbro, tonalite and serpentinite (Schiarizza et al., 1997).

Regional plutonic and volcanic events were episodic during the Cretaceous and Tertiary. The Coast Plutonic Complex (CPC) is the main component of the southwestern Coast Belt, as well as the main granitic intrusion of this region, and marks the southwest corner of the mineral district (Schiarizza et al., 1997). The Bendor batholith is a younger constituent east of the CPC, in the form of an outlier pluton, which runs for 20 km in a northwest-trending direction between the Bralorne fault zone and the Marshall Creek fault (Figure 2). These intrusions comprise granodiorite to quartz diorite, characterized by massive hornblende>biotite>pyroxene and magnetite-titanite, and generally have sharp contacts with a 1 km contact metamorphism halo. A mass of mafic to felsic dikes intrude all of the units. These dikes include 85.7 Ma hornblende porphyry, 86–91 Ma albitite dikes, plagioclase porphyry and lamprophyre. These are all considered to be hypabyssal equivalents of the CPC (Church, 1996).

Dextral strike-slip movement reactivated many of the older northwest-trending faults, especially along the Yalakom fault system, which includes the Marshall Creek, Shulaps thrust, Castle Pass, Bralorne fault zone and Relay Creek faults (Umhoefer and Schiarizza, 1996). These structures postdate the accretionary contractional structures at 67 Ma, but continued to be active through to 40 Ma (Schiarizza et al., 1997).

Metallogeny and Deposit Geology

The previously operating mines in the district are Bralorne, Pioneer, Wayside, Minto, Congress and Silverquick, and surrounding these there are more than 60 mineral occurrences. The variety of mineral occurrences includes Au dominant, Sb dominant, Hg dominant and the occasional Cu-Mo prospect (Woodsworth et al., 1977).

Gold Association

The Au-dominant deposits and occurrences occupy the area along the Bralorne fault zone (Figure 2) between the Bendor batholith and Coast Plutonic Complex. The zone is underlain by both the Bridge River Complex and Cadwallader terrane sedimentary and volcanic units, as well as wedges of ultramafic rocks and ophiolite (Figure 2; Church, 1996). Gold-quartz veins are hosted in the diorite and gabbro of the Bralorne–East Liza ophiolite complex, which is bordered by serpentinite on one side and is within close proximity to the Bendor batholith on the other. The average thickness of the veins is 1 m and they are ribboned with septa of sulphide minerals, sericite and native Au (Leitch et al., 1989). Veins often follow the older albitite dike contacts and the extensive network of faults that are

part of the Bralorne zone (Leitch, 1990). Fuchsite alteration is a prominent feature of this mineralization type, being directly associated with the hydrothermal veins, but found a fair distance from the deposits. The dominant sulphide minerals are arsenopyrite and pyrite, with a lesser amount of sphalerite, galena, chalcopyrite, pyrrhotite and stibnite. There is a high Au/Ag ratio, with Au occurring as free Au, often in association with massive arsenopyrite, which is found next to the veins (Church, 1996). The paragenesis of the Au mineralization begins with deposition in the veins of lean quartz with minor pyrite and fuchsite. The veins are then refractured and refilled with Au- and arsenopyrite-bearing quartz with minor sphalerite, galena, chalcopyrite and tetrahedrite (Figure 3).

Antimony Association

The Sb deposits and occurrences, characterized by the Congress and Minto mines, are found distributed through the central northwest-trending region in Figure 2. Veins are generally smaller than the Au deposits and are discontinuous in the shear zones, have a low Au-Ag ratio, and a larger amount of mixed sulphide minerals (Church, 1996). Cairnes (1937) and Maheux (1989) identified two main styles of mineralization for the Sb deposits; one (Sb-Au-Ag±Hg) with a dominant stibnite phase that is associated with some Au mineralization and a lesser amount of other sulphide phases, while the other (Ag-Au±Sb) is base-metal enriched and has a wider variety of sulphide phases. Examples of the stibnite-dominant mineralization include the Congress and Howard mines, while the base-metal mineralization is seen at the Minto and Olympic mines. The greenstone and sedimentary rocks of the Cadwallader Group host the base-metal–enriched mineralization with veins following the contact between cherty sedimentary
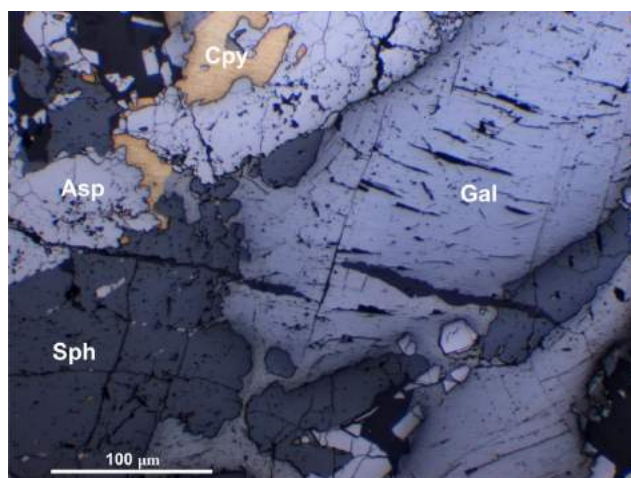
rocks and the diorite dike. The principal sulphide minerals include arsenopyrite, pyrite, sphalerite and jamesonite with minor phases of galena, chalcopyrite, pyrrhotite and stibnite. The paragenetic sequence of the base-metal–type mineralization begins with quartz-ankerite lodes dominated by early- to main-stage pyrite, arsenopyrite, chalcopyrite and sphalerite; the minor sulphide minerals were also deposited during this main stage while quartz, Au and minor base-metal sulphide minerals came in late in the process. The Congress- and Howard-type mineralization is found in shear zones that follow the contact between sedimentary rocks and volcanic units of the Cadwallader Group. Mineralization is made up of fissure fillings and replacement bodies and is discontinuous along the shear zone (Figure 4). Principal sulphide minerals for this mineralization include stibnite, which occurs in sulphide clumps with arsenopyrite, pyrite (Figure 5) and sphalerite, and minor sulphide minerals are galena, tetrahedrite, chalcopyrite, jamesonite, pyrrhotite, cinnabar and native Au (Maheux,
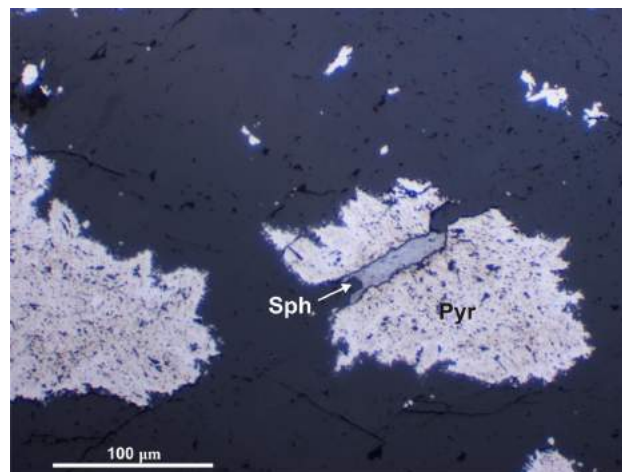
Figure 4. Reflected-light photograph at 5× magnification of the Howard Sb deposit, showing sphalerite in equilibrium with pyrite. Abbreviations: Pyr, pyrite; Sph, sphalerite.

Figure 3. Reflected light photograph at 5× magnification of the Peter vein, showing sulphide mineral equilibria. Notice that all sulphide minerals in this photo are in equilibrium. Late-stage refracturing of the veins by quartz-carbonate has occurred. Abbreviations: Asp, arsenopyrite; Cpy, chalcopyrite; Gal, galena; Sph, sphalerite.

Figure 5. Scanning electron microscope (SEM) image of the Summit deposit, showing arsenopyrite and pyrite in equilibrium. Abbreviations: Asp, arsenopyrite; Pyr, Pyrite.

1989). The mineral paragenesis can be summarized into first-stage quartz-ankerite±calcite with pyrite and arsenopyrite, deposition of quartz and massive stibnite, open space filling by quartz-car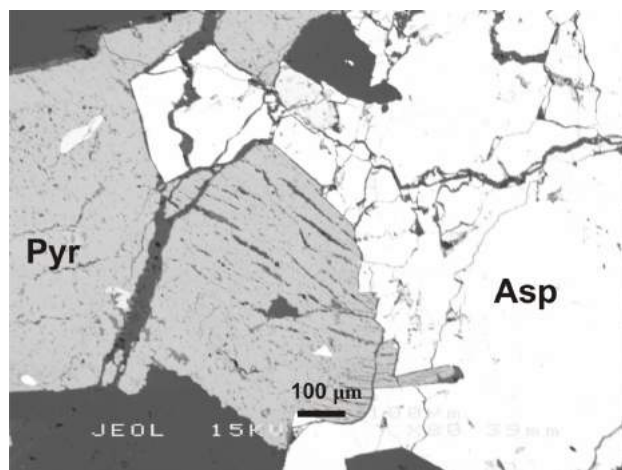bonate with minor tetrahedrite, sphalerite, jamesonite and cinnabar, and late-phase Au associated with stibnite as fracture filling and inclusions.

Mercury Association

Mercury mineralization, characterized by cinnabar, occurs along the Yalakom and Relay Creek fault systems in the north-northeast region of the district. The sedimentary rocks of the Tyaughton Basin and greenstone of the Bridge River Complex underlie these deposits. Cinnabar mineralization in the brecciated conglomerate (Figure 6) is associated with quartz, calcite, limonite and clay minerals. Smeared flakes of cinnabar are also present on the walls and gouges of faults (Silverquick deposit; Church, 1996). Stibnite is also associated with cinnabar, and together they occur in quartz veinlets and as disseminated grains (Manitou deposit; Schiarizza et al., 1997).

Previous Models for Sulphur and Fluid Sources

Possible sources for the mineralizing fluids and S that formed the deposits and occurrences of the Bridge River–Bralorne mineral district included the Coast Plutonic Complex (Leitch et al., 1991a), ophiolite from the Bralorne–East Liza ophiolite complex (Ash, 2001), the Bendor batholith (Church, 1996) and reactivated faults (Schiarizza et al., 1997). Geochronology values from the Bralorne–Pioneer Au veins indicate that the age of mineralization is 67 Ma (Hart et al., 2008). Since the majority of pluton emplacement of the Coast Plutonic Complex occurred around 90 Ma (Leitch et al., 1991a), it is evidently too old to provide heat and fluid sources for mineralization. Additionally, the albitite dikes are also 90–85 Ma (Leitch et al., 1991a), so they are >20 Ma older than mineralization and the Bralorne–East Liza ophiolite, which was thrust into the zone during the mid-Cretaceous deformation (Leitch et al., 1989). As a result, mineralization cannot be directly or genetically related to these features. The Bendor batholith, with an age of 65 Ma, is apparently 2 Ma younger than the mineralization at 67 Ma (Hart et al., 2008), and is therefore unrelated. The only geological event with the same age (67 Ma) as the mineralization is the reactivated dextral strike-slip faults, which are part of the Yalakom fault system (Schiarizza et al., 1997).

Sulphur Isotopes

A S isotopic study was conducted to determine the isotopic signature of S in sulphide minerals, from a wide range of deposits and mineral occurrences throughout the district. Analyses from 25 different mineral occurrences and deposits are presented, encompassing all three mineralization
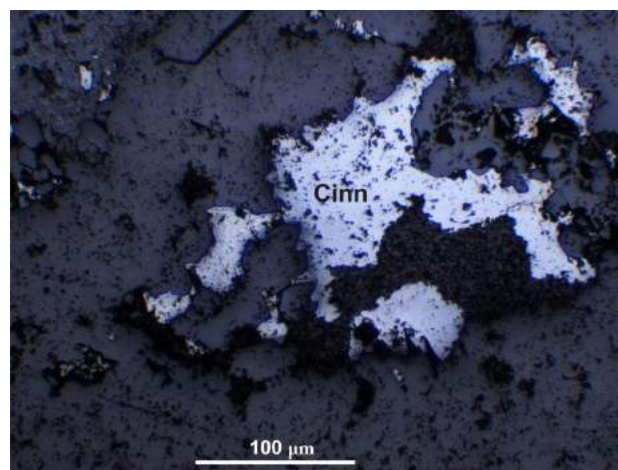

Figure 6. Reflected light photograph at 10× magnification of the Silverquick Hg deposit. Cinnabar is intergrown with specks of wallrock. Cinn: Cinnabar.

types (Figure 2). Most samples had more than one sulphide mineral, and therefore provided an opportunity to obtain more than one isotope analysis from a single deposit. Fifty-four S isotopic analyses are presented in Table 1.

In addition, country rock samples of the main representative units were analyzed for their S isotopic composition in order to provide a comparison point for the mineral isotope data. Nine samples of country rock were taken during fieldwork in June 2008. Samples include CPC; Bendor batholith; biotite schist, basalt, gabbro and greywacke from the Bridge River Complex; basalt and albitite from the Cadwallader Group; serpentinite from the Bralorne ophiolite complex; and the Silverquick Formation shaly sedimentary rocks from the Tyaughton Basin.

Samples were analyzed by the mass spectrometer at the United States Geological Survey (USGS) in Denver, Colorado, and included sulphide minerals from each deposit type and the surrounding country rock (Figure 2). The selected sulphide grains from the deposits include pyrite, sphalerite, arsenopyrite, galena, pyrrhotite, stibnite and cinnabar. Two S extraction methods for whole-rock samples by Tuttle et al. (1986) and Sasaki et al. (1979) were conducted on the country rocks. The analytical process involved a few steps of acid digestion, using a combination of different acids, of the very finely crushed country rocks in order to convert any S present in the rock to Ag_2S and $BaSO_4$, which was then analyzed by the mass spectrometer.

The range of the S isotopic signatures for sulphide minerals of all three deposit types collectively is from +4.3 to –9‰ (per mil; Table 1). The Au deposits and occurrences range from +4.3 to –2.7‰ with a mean of +1, Sb-associated mineral occurrences from +0.2 to –9‰ with a mean of –3.8‰ and Hg at –6.2‰ (Figure 7). The Sb deposits and occurrences had the most samples from a wide sampling area, which could explain the wider range in values, whereas the

Table 1. Sulphur isotopes (listed as ‰ relative to Canon Diablo Triolite (CDT)) of deposits in the Bridge River–Bralorne mineral district.

Sample ID	Deposit	Mineral	$\delta^{34}S$	Sample ID	Deposit	Mineral	$\delta^{34}S$	Sample ID	Deposit	Mineral	$\delta^{34}S$
Au-dominant deposits											
PIEBITER	Piebiter	py	0.0	PLS	Peerless	py	0.1	MINTO	Minto	sph	-1.1
PNE3	Pioneer	py	3.5	MINTO	Minto	py	-0.8	OLY COR 7	Olympic Core	sph	-4.1
BRALORNE	Bralorne	py	3.2	RBS	Robson	py	-3.1	LS3	Lucky Strike	pyrr	-3.7
PNEX2	Pioneer Extension	py	2.9	KV2	Kelvin	py	-5.9	KV2	Kelvin	gal	-8.6
PETER	Peter Vein	py	-1.7	LS1	Lucky Strike	py	-2.7	GR2	Grey Rock	gal	-2.5
LGM1	Little Gem	py	-4.5	GR8	Grey Rock	py	0.0	GR8	Grey Rock	gal	-2.5
STD2	Standard	stib	-1.7	GR2	Grey Rock	py	-0.6	LYJI1	Lucky Jem	asp	-2.7
PETER	Peter Vein	sph	-3.2	LYJ1	Lucky Jem	py	-2.2	MINTO	Minto	asp	-0.7
BRALORNE	Bralorne	asp	1.4	OLYM2	Olympic	py	-0.8	LS2	Lucky Strike	asp	-3.9
PNE2	Pioneer	asp	4.3	99-8	99-8	py	-3.5	LS3	Lucky Strike	asp	-4.0
PNE3	Pioneer	asp	3.5	MM3	Mary Mac	stib	-8.6	RBS	Robson	asp	-4.9
PNE4	Pioneer	asp	2.5	CONG2	Congress	stib	-4.8	99-8	99-8	asp	-2.8
LGM1	Little Gem	asp	-5.5	MM5	Mary Mac	stib	-9.0	LOVE OIL	Love Oil	asp	-1.5
				GR5	Grey Rock	stib	-3.4	BBC35	BBC-35	pyrr	-2.2
Sb-dominant deposits				LS1	Lucky Strike	stib	-7.5				
SMT1	Summit	py	-5.9	CONG2	Congress	stib	-4.7	Hg-dominant deposit			
SMT2	Summit	py	-6.0	SMT2	Summit	sph	-4.3	SQ2	Silverquick	cinn	-6.2
OLYCOR6	Olympic Core	py	-6.3	RBS	Robson	sph	-4.2				
OLYCOR7	Olympic Core	py	-4.9	LS1	Lucky Strike	sph	-3.4				
OLYCOR7	Olympic Core	py	-5.1	PLS	Peerless	sph	-0.6				
OLYCOR6	Olympic Core	py	-5.8								

Abbreviations: py, pyrite; stib, stibnite; asp, arsenopyrite; sph, sphalerite; pyrr, pyrrhotite; gal, galena; cinn, cinnabar

Hg deposit only had one sample and one value. The majority of the isotopic values from the Au deposits occur above 0‰, while the Sb values exhibit a few different cluster points, one occurring around –6‰, one at –2.3 to –4.5‰ and one around –1‰. There are also outliers at –8.8 and –9‰ for Sb mineralization and –2 and +4.1‰ for Au mineralization. When separated according to deposit type, the data show a clear pattern of a decrease in the heavier isotope, which is movement toward lighter ratios, from Au, through Sb, to Hg deposits (Figure 7). The distribution of the isotope patterns correlates with the deposit-type distribution, thus showing a spatial zonation from west to east of a decrease in the heavier isotope.

The whole-rock signatures of the nine country-rock units yield a large range, from –21.7‰ for the Silverquick Formation, to +14.1‰ for the Congress basalt (Table 2; Figure 8). The sedimentary units (Silverquick Formation, Bridge River schist and Bridge River greywacke) display highly negative ^{34}S values at –21.7‰, an average of 17.65‰ and an average of –17.53‰, respectively. The two intrusions, the Coast Plutonic Complex and the Bendor batholith, yielded values of –0.4‰ and –1.7‰, respectively. The serpentinite yielded four measurements, with an average of +4.45‰, exhibiting a slight enrichment in ^{34}S, but still within the magmatic range (Ohmoto and Rye, 1979). The two basalt units, Cadwallader basalt and Bridge River basalt, do not show the same similarity in S isotope values that the other country rock groups (intrusions and sedimentary rocks) do. The Cadwallader basalt produced values with an average of +13.45‰,
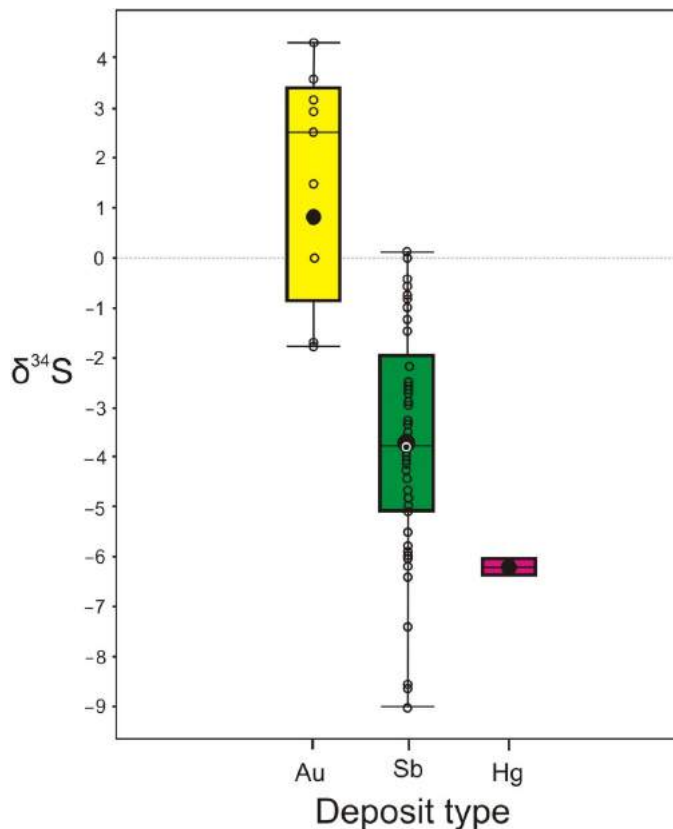

Figure 7. Box-and-whisker plot of deposit S isotope signatures showing dispersal of data throughout ranges. Mineralization type presented from west to east, showing the decrease in ^{34}S spatial zonation pattern.

while the Bridge River basalt has values with an average of +3.4‰.

The isotopic signatures for the country rock are overall consistent with previous studies (Ohmoto and Rye, 1979) on S isotope reservoirs, and have the typical signatures one would expect. The one exception is the Cadwallader basalt, which has a more positive ^{34}S than the archetypal basalt (usually closer to 0‰).

Geothermometry

Sulphur geothermometry is the measurement of the temperature of equilibration, and is based on the fractionation of S isotopes between two compounds, such as PbS and ZnS (Seal, 2006). For this calculation to be accurate, the compounds must be in equilibrium with each other, and must also not have undergone re-equilibration or alteration. The temperature dependence of the fractionation factors must be known and pure minerals must be separated for isotopic analysis (Seal, 2006). The temperature is calculated by measuring the difference in the ^{34}S values of two sulphide minerals in equilibrium and plotting the result on a graph showing the equilibrium constant and isotope fractionation factor as a function of temperature. Pyrite is gen-

Table 2. Sulphur isotopes (listed as ‰ relative to CDT) of country rock in the Bridge River–Bralorne mineral district.

Sample ID	Country Rock Member	Sulphide type	δ^{34}S
WAYW3 SEDS	Bridge River Complex greywacke	mono	-19.9
WAYW3 SEDS	Bridge River Complex greywacke	di	-12.7
WAYW3 SEDS	Bridge River Complex greywacke	total	-20.0
WAYW2 BASALT	Bridge River Complex basalt	mono	2.3
WAYW2 BASALT	Bridge River Complex basalt	total	4.5
WAYW1 GABBRO	Bridge River Complex gabbro	mono	1.5
SERP1	Bralorne–East Liza ophiolite complex serpentinite	mono	4.3
SERP1	Bralorne–East Liza ophiolite complex serpentinite	di	4.6
SERP2	Bralorne–East Liza ophiolite complex serpentinite	mono	4.2
SERP2	Bralorne–East Liza ophiolite complex serpentinite	total	4.7
CONG BASALT	Cadwallader Group basalt	mono	13.4
CONG BASALT	Cadwallader Group basalt	mono	14.1
CONG BASALT	Cadwallader Group basalt	total	12.9
COAST	Coast Plutonic Complex	mono	-0.4
SQF1-W	Silverquick Formation shale	di	-21.7
BENDOR	Bendor batholith	total	-1.7
CHALCO SCHIST	Bridge River Complex schist	mono	-17.8
CHALCO SCHIST	Bridge River Complex schist	di	-16.2
CHALCO SCHIST	Bridge River Complex schist	total	-17.5
CHALCO SCHIST	Bridge River Complex schist	total	-17.7
CHALCO SCHIST	Bridge River Complex schist	total	-19.2

Abbreviations: mono, monosulphide; di, disulphide; total, total sulphur

erally not as reliable as it tends to be in equilibrium across a range of temperatures (Ohmoto and Rye, 1979; Rye and Ohmoto, 1974; Seal, 2006). For this exercise, pyrite-galena and pyrite-sphalerite will be used as there are no sphalerite-galena pairs.

The data are presented in Table 3. It shows that there are no consistencies in temperatures between the mineralization
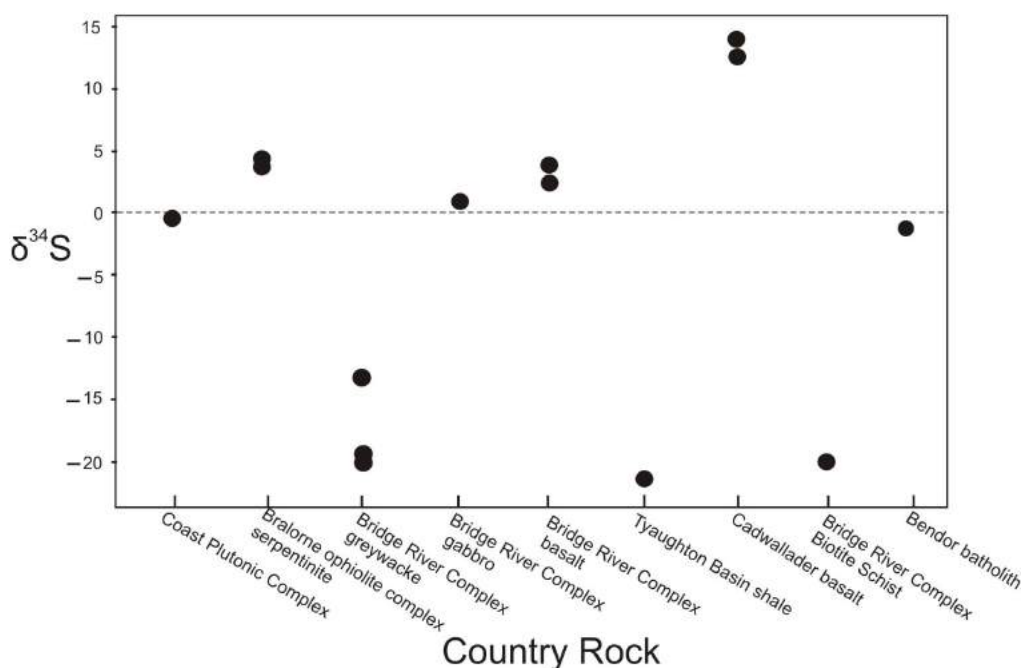

Figure 8. Plot of country rock isotope signatures. Samples organized from west to east.

Table 3. Temperature estimates using the sulphide-pair method from Seal (2006).

Sample ID	Deposit	Mineral Pairs δ³⁴S		min₁_min₂	lnαmin–H₂S	×10⁶	×10⁶/min₁_min₂	SQRT	TEMP
		Gal	Py						
KV2	Kelvin	-8.6	-5.9	2.7	1.03	1030000	381481.4815	617.6419	344.4919
GR8	Grey Rock	-2.5	0	2.5	1.03	1030000	412000	641.8723	368.7223
GR2	Grey Rock	-2.5	-0.6	1.9	1.03	1030000	542105.2632	736.278	463.128
		Py	Sph						
PLS	Peerless	0.1	-0.6	0.70709	0.3	300000	424274.3777	651.3635	378.2135
SMT2	Summit	-6.0	-4.3	1.70000	0.3	300000	176470.5882	420.084	146.934
MINTO	Minto	-0.8	-1.1	0.37016	0.3	300000	810453.8825	900.2521	627.1021
LS1	Lucky Strike	-2.7	-3.4	0.65468	0.3	300000	458240.633	676.9347	403.7847
OLYCOR7	Olympic Core	-5	-4.1	0.91423	0.3	300000	328145.7142	572.84	299.69
PETER	Peter Vein	-1.7	-3.2	1.52718	0.3	300000	196440.3296	443.2159	170.0659
RBS	Robson	-3.1	-4.2	1.2	0.3	300000	254698.3533	504.6765	231.5265
		Py	Stib						
LS1	Lucky Strike	-2.7	-7.5	4.8	1.15	1150000	240830.6404	490.745	217.595

Abbreviations: Gal, galena; Py, pyrite; Stib, stibnite; Sph, sphalerite; SQRT, square root

types. The one value for Au is extremely low at 170°C. Antimony mineralization types display a very large range, from 146 to 627°C, without clustering around any one temperature. The calculated temperature values for these deposits and occurrences are inconsistent with the known models for not only this district (Maheux 1989; Leitch et al. 1991b), but for orogenic Au deposits in general (Groves et al., 2003).

Figure 9 shows previously calculated fluid-inclusion temperature data for the mineralization types in the district. The Au deposits are hot, ranging from 280 to 365°C, the Sb deposits are cooler with a range of 220 to 300°C and Hg deposits are the coolest with mineralizing fluid temperatures around 190°C. These temperatures are more within the expected range for this type of hydrothermal system. There are many inconsistencies between the data in Figure 9 and Table 3. The Au temperature in Table 3 (using sulphide pairs) is 200°C cooler than the temperatures in Figure 9 (using fluid inclusions). The Sb mineralization displays a much smaller range in Figure 9 than in Table 3, but there is a small overlap between the two ranges; Robson (RBS) in Table 3 has a calculated temperature of 231°C, which is on the lower end of the Figure 9 range. The main problem with the data in Table 3 is that it was calculated using sulphide pairs that are not the recommended pairs (sphalerite and galena), and all pairs involved pyrite, which is the least reliable of the sulphide minerals used for that method of calculation. Unfortunately, the pairs used were the best possible pairs out of the analyzed sulphide minerals.

Discussion

Sulphur isotopes can be extremely useful for establishing the genesis of an ore deposit, and can additionally provide information on the temperature of mineralization, chemical conditions and mechanisms of ore deposition and the source of the S in the ore-forming fluid (Ohmoto and Rye, 1979). A previous S isotope study on the Bralorne–Pioneer Au deposit by Leitch et al. (1991b) was interpreted to show that the fluids were primarily magmatic and metamorphic, but had a component of late-stage meteoric mixing.

The S isotopic signatures of the mineralization types and their distributions from west to east across metal zones that characterize the district can result from an increasing reaction of the mineralizing fluids with the S in the country rock. As there are a variety of country rocks surrounding the mineralization types, there are also a variety of S
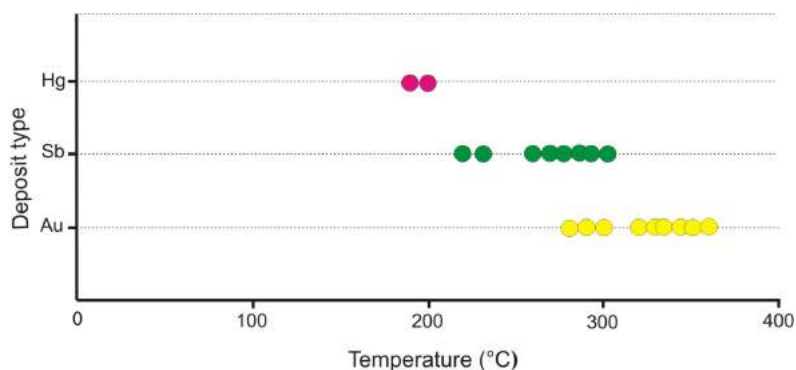
Figure 9. Temperatures of deposits calculated from fluid-inclusion studies by Maheux (1989) and Leitch et al (1991b).
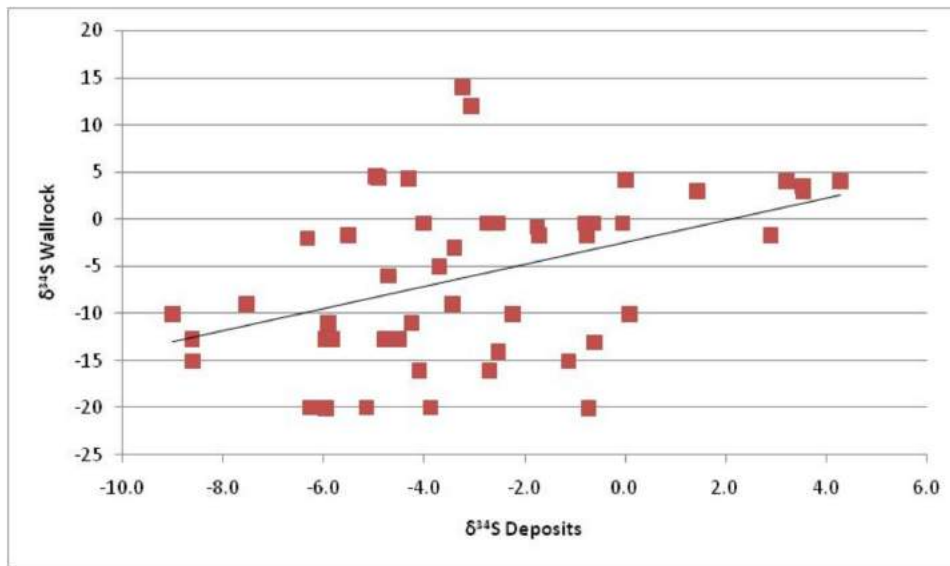
Figure 10. Graph showing the correlation between country rock and deposit S isotope signatures.

mineral occurrences get the majority of their S from the adjacent country rocks.

A similar study was performed on analogous Au deposits in southeastern Alaska on the west side of the Coast Plutonic Complex, which also found a correlation between the S isotopic ratios of the country rock and the Au mineralization (Goldfarb et al., 1997). Gold veins dated at 55–66 Ma postdate the initial period of collision by 100 Ma, and were emplaced at depths of 3–10 km with vein formation temperatures of 225–375°C. Deposits that were hosted in diorite had values that clustered around 0‰, while veins hosted in argillite showed ranges of –6 to –12‰. The conclusion of this study was that the nearby sedimentary rocks provided the source for the majority of the S in the ore-bearing fluids, with possible igneous rock-hosted contributions. While Goldfarb et al. (1997) stated that there was a possibility of a small fluid contribution from the proximal calcalkaline intrusions, it was also concluded that on a broader scale, this hydrothermal activity could be related to rising crustal temperatures associated with ongoing collision, metamorphism and crustal dehydration. Considering the Bridge River–Bralorne mineral district is located on the eastern edge of the Coast Plutonic Complex, which was a magmatic arc that continues up into southern Alaska, it is likely that the metamorphism that generated crustal dehydration occurring in southeastern Alaska also took place in southwestern BC, thus providing metamorphogenic crustal hydrothermal fluids.

sources. The assumption was made that there would be mixing of S from different sources, combining to produce a unique S isotope value. It seems unlikely that as fluid travels along a pathway, it only scavenges S from one source, unless one rock type is enriched in S or that S is more accessible/soluble. Mixing of the S between two very different isotopic sources, for example, serpentinite (+4.4‰) of the Bralorne ophiolite complex and greywacke of the Bridge River Complex (–19‰), would result in a ^{34}S somewhere in between those two values, depending on the fluid chemistry at the time.

To establish the contributions that country rock S makes toward the S in the sulphide minerals of the deposits, deposit isotope values were assigned to its country rock host value. In the case where there was more than one country rock, a combined value was calculated. This was done using geological information from Maheux (1989), Leitch et al. (1991b), Church (1996), Schiarizza et al. (1997) and Ash (2001), and is displayed in Figure 10. The result generates a positive slope, showing a correlation between the country rocks and the mineralizing fluids, emphasizing that the country rock S isotope signature affects the deposit isotope signature. The decreasing ^{34}S pattern in Figure 7 can be interpreted to suggest that there is an increase in a reduced S source, which is enriched in ^{33}S over ^{34}S. Since reduced S sources are generally sedimentary in origin (Ohmoto and Rye, 1979), this means an increase in sedimentary rock interaction from west to east is likely. The temperature data in Figure 9 also shows a distribution from west to east, with fluids hotter in the west and cooler in the east. Therefore, the trend from west to east from Au deposits through to Hg deposits is a general trend that results from higher amounts of fluid–country rock interactions and indicates that the

A metamorphic origin of ore-forming fluids has been proposed at a number of large-scale orogenic lode-Au deposits around the world, including the Mother Lode district in the North American Cordillera and Macraes Flat in the Otago Province, New Zealand. Nitrogen, hydrogen and oxygen isotope studies indicated that metamorphic dehydration reactions of subduction-accretion complexes along the North America Cordillera resulted in dilute-aqueous, carbonic fluids (Jia et al., 2003). A S isotope study on the Macraes Flat Au deposit in the Otago Province found that the ^{34}S of the sulphide minerals from the deposit had a narrow range of –3 to –1‰, while the Otago schist had a range of –6 to +6‰, suggesting that the S was derived from the schist (Craw et al., 1995). A later study discovered a depletion in ore-forming elements between the greenschist and amphibolite facies

rocks in the Otago schist, and an enrichment in the same elements in the orogenic Au deposits in Otago (Pitcairn et al., 2006), suggesting that the metamorphically derived ore-forming fluids scavenged the elements from those rocks, depositing them further along the fluid pathway.

From the geological and S isotope information in the Bridge River–Bralorne mineral district, it can be assumed that there is one fluid source for all three deposits, with the Au deposits the closest to this source, in relation to the other mineralization types, the Sb an intermediate distance and the Hg the farthest away. The reactivated dextral strike-slip faults were active at the time of mineralization (67 Ma). Therefore, they would provide the perfect fluid conduits for a deeper crustal, metamorphic source of fluids, which according to the correlation between the country rock S and deposit S, was closest to the Au deposits and occurrences, then travelled up and outwards, toward the Sb and Hg occurrences. The temperature data (Figure 9) also supports this conclusion, as it shows the Au mineralization formed from the hottest fluids, Sb from the intermediate and the Hg from the coolest.

The initial ^{34}S of the fluids may have started out at +4‰, and as this fluid travelled up the fluid conduits, it interacted with the country rock S, and evolved its ^{34}S. Since the S in the fluids forming the Au mineralization have had the least opportunity to react with the S in the country rock, and the dominant rock type along the Bralorne fault zone is gabbro, the ^{34}S is closest to +4‰, only deviating a small amount from this value, which is to be expected as reactions will occur between the fluid and the country rock when a fluid travels along its path. The Sb mineralization has a more negative ^{34}S than the Au, which is a result of a higher amount of S sourced from the basalt and sedimentary-dominant country rocks along the Hg fault zones. The Hg mineralization has the overall most negative ^{34}S out of the three mineralization types; consequently, the fluids have purloined the most S from the country rocks, which are sedimentary rocks from the Tyaughton Basin.

Conclusions

The Bralorne–Bridge River mineral district is one of the most significant historical lode-Au producers in BC, and regionally displays a characteristic metal zonation from west to east of Au through Sb- to Hg-associated mineralization. Each mineralization has a characteristic range of ^{34}S values, from +4.3 to –2.7‰ for Au, from +0.2 to –9‰ for Sb and –6.2‰ for Hg that display a decreasing ^{34}S pattern from west to east. When the deposit sulphide mineral ^{34}S values are compared with their respective hostrocks, a correlation was found that demonstrates an increasing reaction of the country rock S with the S in the fluids and reflects the different types of hostrocks. When the S isotope patterns are combined with the cooling temperature trend of miner-

alizing fluids from west to east, it provides evidence of one fluid source for the three dominant types of mineralization in the district.

The deduction of a fluid source for this region is similar to the crustal continuum model (Groves et al., 1998), which states that Sb and Hg mineralization are higher crustal, epizonal equivalents to the mesozonal orogenic Au deposits that all formed from one fluid source that travelled along the same fluid pathway. Assuming this model is true to this district, there is a possibility that there are hypozonal Au deposits somewhere in the region underneath Sb and Hg deposits in the Bralorne–Bridge River mineral district.

In conclusion, a single, deep-crustal fluid source for all three types of deposits flowed up along reactivated strike-slip faults, scavenging S from the country rock as it went. Therefore, there are different S sources for each deposit type, but each type has its own distinctive ^{34}S range, making it identifiable. This impacts the approaches to regional exploration strategies as the most prospective Au deposits will have a more positive ^{34}S, which can easily be determined.

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