

# Blackdome Eocene epithermal Ag-Au deposit, British Columbia, Canada—nature of ore fluids

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July '87

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## Synopsis

The Eocene, epithermal Ag-Au-(Sb-Cu-Fe-Zn-Pb-S-Se-As)-silica deposits of the Blackdome property in southern British Columbia, Canada, have been the subject of fluid inclusion studies and stable isotope analyses. Veins with precious-metal mineralization are hosted by a suite of calc-alkalic volcanic rocks. The deposits were developed when meteoric groundwaters penetrated fissures 0.5–1.1 km below surface into the volcanic pile. A partly vented, boiling geothermal system resulted, and the aqueous fluids effected phyllosilicate plus K-feldspar alteration of the host reservoir rocks. Pervasive propylitization of the host volcanics characterizes this former geothermal field. The geothermal fluids were characterized by low salinities—in the order of 0.21–2.07 wt% NaCl equivalent—densities of 0.720–0.810 g/cm<sup>3</sup>,  $\delta^{18}\text{O}$  values of –6.8 to –8.8‰ (SMOW) and  $\delta\text{D}$  values of –125 to –134‰ (SMOW). Oxygen isotope exchange during hydrative metasomatism caused a positive shift away from the 'meteoric line'. A minor, positive shift in the  $\delta\text{D}$  values, away from the value of the parent meteoric water, might have been due to loss of hydrogen from the vented system, to selective hydrogen metasomatism of the wallrocks or both. The Blackdome deposits clearly belong to the adularia-sericite-type group of volcanic-hosted epithermal precious-metal deposits.

Epithermal precious-metal veins have become increasingly desirable as exploration targets within the last decade. Unfortunately, few northern Cordilleran examples have been completely documented. Epithermal gold lode deposits in the Canadian Cordillera were discussed recently in an article by Nesbitt and co-workers.<sup>1</sup> The Blackdome property in British Columbia hosts a Tertiary, epithermal Ag-Au vein system analogous to the types that are found throughout the western U.S.A. and Mexico, as described by Buchanan.<sup>2</sup> The present study discusses the nature and origin of the ore fluids in the Blackdome system on the basis of evidence from fluid inclusions and stable isotope data.

The Blackdome property is located in south-central British Columbia, some 70 km WNW of the town of Clinton. It is accessible by 140 km of gravel road leading west from provincial highway 97, 18 km north of Clinton. The approximate geographical centre of the property is at 51° 20' north and 122° 29' west (Fig. 1). The mine area contains a large epithermal precious-metal system with numerous mineralized quartz veins within an area that measures 4500 m × 1500 m. The initial reserves on the property were delineated within the so-called no. 1 vein system. Other vein systems do occur on the property, but limited data are available on these.

Manuscript first received by the Institution of Mining and Metallurgy on 21 July, 1986; revised manuscript received on 4 December, 1986. Paper published in *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)*, 96, February 1987. © The Institution of Mining and Metallurgy 1987.

Blackdome mine commenced production in May, 1986, and has a projected output of 40 000–45 000 oz gold and 220 000 oz silver per year.

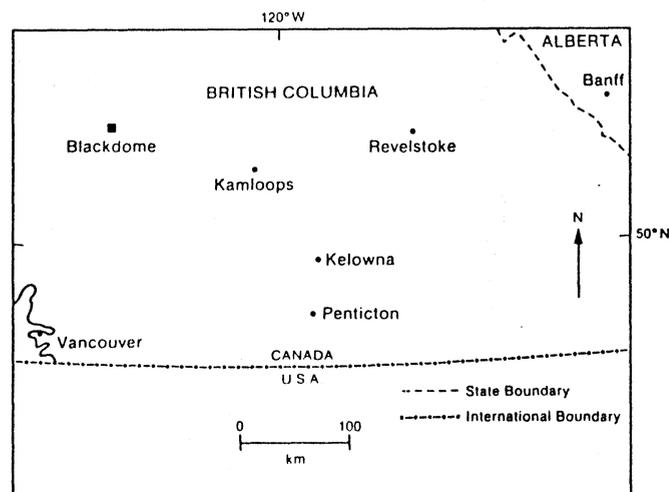


Fig. 1 Location of Blackdome Ag-Au deposit, British Columbia, Canada

## Previous work

Church<sup>3</sup> gave the first summary account of the nature of the Ag-Au mineralization at Blackdome. Other authors, such as Panteleyev<sup>4</sup> and Sutherland Brown,<sup>5</sup> have emphasized the close analogy between the Blackdome deposit and epithermal deposits of the western U.S.A. Panteleyev<sup>4</sup> also suggested that the Blackdome deposit probably formed at a depth of about 0.5 km, above the boiling level.

The most recent account of the Blackdome deposit was presented by Reeve and Rennie,<sup>6</sup> whose work provided valuable background for the present study. They stated that the proven to possible reserves in 1985 comprised a total of 184 695 t with grades of 15.1–34.6 g/t Au and 91.3–204.9 g/t Ag at a cutoff grade of 8.5 g/t Au. Their data also imply Au/Ag ratios of 0.17–0.28. Nesbitt and co-workers<sup>1</sup> stated recently that the ratios of such deposits in the Cordillera were typically in the range 0.05–0.2.

## General geology

The geology of the Blackdome area is illustrated in Fig. 2. The property is underlain by a localized suite of early- to mid-Tertiary volcanic rocks and associated volcanoclastic sediments, cut by narrow intermediate to mafic dykes. Lower Miocene to Upper Oligocene porphyritic basalt flows, which cap Blackdome Mountain, are the youngest rocks of the sequence. Underlying the basalts is a sequence of Eocene porphyritic andesite flows. A thin, irregular and discontinuous clastic unit underlies the porphyritic andesite. This unit, which is up to 30 m thick, varies from a volcanoclastic sandstone to coarse agglomerate with mafic bombs up to 40 cm long. A 'chaotic rhyolite' unit, which underlies the porphyritic andesite, is actually a mixture of

rhyolitic flows, tufts and breccias, as well as local lenses of volcanic wacke. Underlying the 'chaotic rhyolite' and beneath the clastic horizon at the base of the dacite unit, north and northeast of the 'chaotic rhyolite', is a series of Eocene porphyritic dacite flows. Andesite flows (with propylitic alteration), tufts and agglomerate underlie the dacite unit, constituting the oldest units on the property.

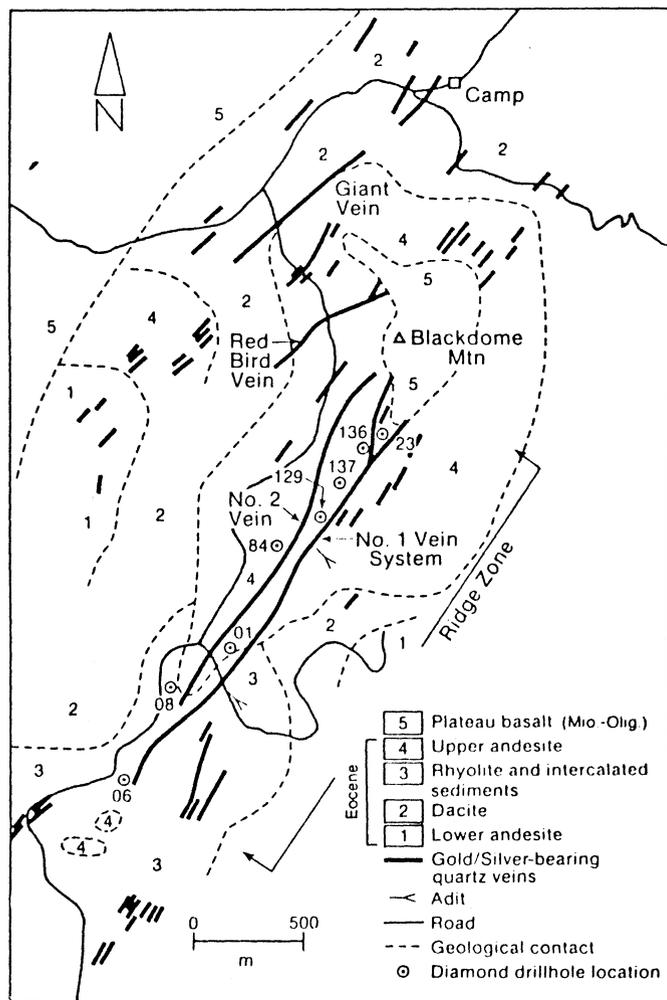


Fig. 2 General geology of Blackdome Ag-Au deposit

The volcanic horizons strike NNE with shallow 10–20° dips to the southeast. Tension fractures are the loci of the epithermal, precious metal-bearing veins. The fractures were, apparently, the result of uplift by volcanic doming. Minor normal faulting effects dislocation of some units and preserves some erosional remnants of younger rocks.<sup>7</sup>

Major- and trace-element analyses performed by the authors suggest a calc-alkaline affinity for the volcanic rocks and also that they originated within a volcanic arc system. This volcanic arc constituted part of Stikinia (as defined by Monger and co-workers<sup>8</sup>), an allochthonous component of the Canadian Cordillera that was accreted on to the North American continent.

### Vein mineralogy

The Blackdome deposits are composed of stockworks of quartz veinlets and zones of silicification in zones of fracturing that extend peripherally as much as 15 m from the principal fault zones. The quartz-rich gangue carries 2% (modal) or less of a complex association of fine-grained, anhedral opaques. The minerals observed to date are native gold, native silver, electrum, acanthite, freibergite, several unidentified silver sulphosalts, aguilarite (Ag<sub>4</sub>SeS) and

naumannite (Ag<sub>2</sub>Se), with minor pyrite, pyrrhotite, marcasite, chalcopite, bornite, arsenopyrite, sphalerite, galena and tetrahedrite. Minor supergene digenite and covellite are also observed. Goethite and pyrolusite are commonly present as secondary coatings on fracture surfaces in the veins. Quartz appears to have been precipitated both early and late in the vein paragenetic sequence and was also coeval with the main, metalliferous stage of mineralization. Gold and electrum appear to be late phases in the paragenetic sequence and to postdate the precipitation of the sulphides and selenides in the ores.

### Hydrothermal alteration

The vein systems are hosted by andesites and rhyolitic rocks that exhibit pervasive propylitic alteration with the development of a replacive association of epidote (var. pistacite)-chlorite-carbonate. The propylitic alteration appears to be a broader-scale feature and is not limited to those areas invaded by metalliferous veins. The rocks of the rhyolitic unit also frequently exhibit strong, localized argillic alteration. Work is currently in progress on the assemblages of the clay-phyllosilicate alteration suite, which also appears not to correspond exactly to the spatial extent of the ore zones.

The ore veins are characterized by a distinct alteration halo, which can extend 1–15 m beyond the veins. The alteration zone is characterized by noticeable bleaching of the propylitized host volcanics and by the development of a replacive assemblage of quartz-adularia-sericite-kaolinite-chlorite-montmorillonite-illite.

### Salinities, temperatures and pressures of ore fluids

#### Experimental techniques

Doubly polished quartz plates from massive and some vuggy sectors of the veins were prepared for microscopic and microthermometric studies. The polished plates were first examined under the petrographic microscope and inclusions suitable for microthermometric investigation were selected. Microthermometric experiments were carried out on a Chaimeca model VT2120 heating and freezing stage, which was calibrated by use of a series of standards supplied by the Centre de Recherches Pétrographiques et Géochimiques, Nancy, France. Analytical reproducibilities were ±0.1°C for freezing and ±3°C for heating at about 300°C.

#### Description of inclusions

Primary, secondary and pseudo-secondary inclusions were identified in the quartz samples. The size range of the inclusions (longest axis) varied from less than 1 to more than 180 μm. The average size of the inclusions was less than 1 μm in most chips, but some of the samples contained inclusions 1–3 μm long. The inclusions were commonly equant and amoeboid in shape, but irregular, subequant and negative crystals were also observed. Three types of inclusion were observed: type (1) (dominant), two-phase, liquid-vapour inclusions with an estimated 5–40 vol% vapour—these homogenized in the liquid phase; type (2), two-phase, vapour-liquid inclusions that contained an estimated 10 vol% or less liquid phase—these inclusions constituted only a minor portion of the total and may represent entrapped vapour within a boiling or an effervescing system; and type (3), liquid-dominated inclusions containing variable amounts of the vapour phase, much like the type (1)—this type of inclusion is characterized by the presence of unidentified daughter crystals that are colourless and birefringent and commonly exhibit an acicular habit.

The common coexistence of both liquid- and vapour-rich inclusions with variable filling ratios within the same section was considered to be indicative of boiling or effervescence in the hydrothermal system. CO<sub>2</sub>-bearing inclusions were not identified during the petrographic study or during freezing experiments, which indicates a CO<sub>2</sub> content of less than 0.1 mol%.<sup>9</sup>

### Salinities and densities of ore fluids

The salinities of the fluid inclusions were determined by the freezing-point depression technique. The inclusions used in the freezing experiments were generally greater than 15 μm in diameter. Freezing experiments were carried out primarily on type (1) inclusions, but some type (3) inclusions were also utilized.

In general, the inclusions were chilled to -60 to -70°C to ensure that the system was totally frozen. Most inclusions showed deformation of the vapour bubble between -35 and -42°C. The first melting-point temperature, T<sub>e</sub>, occurred in most inclusions between -0.15 and -1.14°C.

The salinities of the fluids are, thus, inferred to lie between 0.21 and 2.07 wt% NaCl equivalent.<sup>10</sup> The complete experimental results are presented in Table 1 and plotted in Fig. 3. It is clear from the results that the Blackdome hydrothermal fluids were of low salinity and exhibited only a very limited variation in their dissolved ion contents. The densities of the ore fluids were probably in the range 0.720-0.810 g/cm<sup>3</sup>.<sup>11,12</sup>

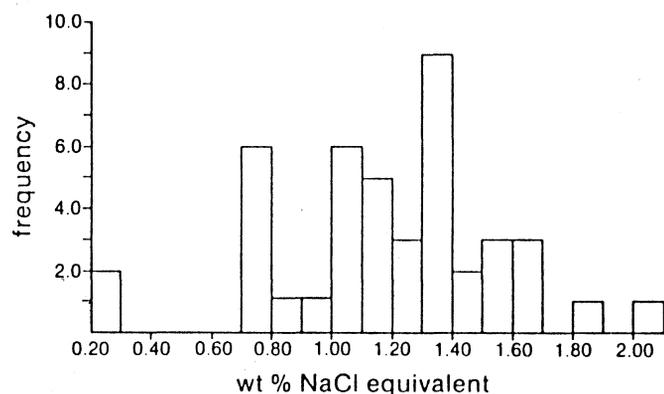


Fig. 3 Histogram of salinity data obtained from fluid inclusions in quartz from Blackdome Ag-Au deposit

### Temperatures, pressures and depth of ore formation

The homogenization temperatures of both primary and secondary inclusions were measured (Table 1 and Fig. 4). The data suggest that the quartz components of the paragenetic sequence record only one peak thermal stage, which varies between 260 and 295°C. A few higher temperatures of 308 and 313°C were observed. It is felt, however, that the data

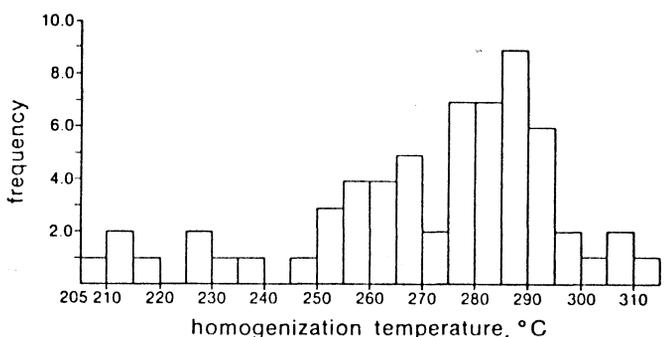


Fig. 4 Histogram of homogenization temperatures obtained from fluid inclusions in quartz from Blackdome Ag-Au deposit

Table 1 Temperature and salinity data for hydrothermal fluids in Blackdome Au-Ag deposit, British Columbia

Quartz sample no.	Origin of fluid*	T <sub>h</sub> † °C	T <sub>0</sub> ‡ °C	Salinity, wt% NaCl equivalent
139-153	P	235	-0.65	1.17
139-158	P	213	-0.90	1.56
	P	209	-0.75	1.30
	S	—	-0.65	1.17
137-51.6	P	279	-0.15	0.26
	P	268	-0.40	0.70
	S	276	-0.45	0.79
	S	281	-0.40	0.70
137-55	P	273	-0.60	1.04
148-164.7	P	299	-0.70	1.22
	P	285	-0.60	1.04
	S	230	-0.60	1.04
	S	236	-0.80	1.39
148-165	P	279	-0.43	0.75
136-43.5	P	286.5	-0.95	1.64
135-60	P	258	-0.12	0.21
	P	250	—	—
	P	253	—	—
84-29.5	P	264	-0.75	1.30
84-30.5	P	290	-0.90	1.56
	P	289	-0.78	1.40
	P	295	-0.83	1.44
	P	287	—	—
84-30.1	P	215	—	—
	P	219	—	—
	P	225	—	—
84-33.5	P	294	—	—
	P	301	—	—
	S	276	—	—
	S	286	—	—
84-34.2	P	280	—	—
	P	294	—	—
	P	256	-0.60	1.04
30-11.4	P	313	-0.50	0.90
	P	298	-0.45	0.79
	S(?)	306	—	—
30-11.8	P	307	-0.51	0.91
	P	292	-0.45	0.79
	P	287	-0.47	0.84
30-13.9	P	263	-0.90	1.56
	P	268	-0.60	1.04
	P	280	-0.65	1.17
	P	263	-0.70	1.22
	P	289	—	—
23-22	P	293	-0.65	1.17
08-30.5	P	278	-0.94	1.63
	P	265	—	—
08-32.2	P	285	-0.80	1.39
	P	289	-0.75	1.30
	S	284	-0.75	1.30
	S	276	-0.70	1.22
06-17.3	P	283	-0.94	1.63
	P	267	-1.04	1.89
06-15.0	P	274	—	—
	P	278	—	—
	P	280	—	—
01-10.3	P	249	-0.75	1.30
	P	258	-0.75	1.30
01-12.5	P	263	-0.60	1.04
	P	258	-0.65	1.17
	P	255	-0.75	1.30
01-15.3	P	280	-1.14	2.07

\*P, primary inclusion; S, secondary inclusion.

†Homogenization temperature.

‡Last-ice melting temperature.

are insufficient to support the postulation of a number of distinct temperature regimes. Some lower temperatures of 209, 215 and 226°C were obtained, but again the sample population is too small to substantiate the postulation of a distinct lower-temperature regime.

The coexistence of liquid-rich and vapour-rich inclusions suggests boiling. The inferred occurrence of boiling would obviate the need for pressure corrections to the homogenization temperatures. The temperatures and pressures that were determined from the inclusions would then represent the true trapping temperatures and pressures of the inclusions. The pressures that were deduced from coexisting liquid-rich and vapour-rich inclusions were between 46 and 85 bar, which corresponds to an approximate maximum depth of ore deposition of between 0.5 and 1.1 km below the surface of the volcanic field.<sup>11</sup> This conclusion is based on the concept of the veins constituting an episodic, open, vented, hot spring/geyser system whose fluid pressures would have been dominantly hydrostatic rather than lithostatic.

### Oxygen and hydrogen isotopic composition of ore fluids

#### Experimental techniques

Selected samples of quartz and their fluid inclusion waters were analysed for oxygen and hydrogen isotopes. Samples of present-day waters were also analysed for reference purposes. The standard BrF<sub>5</sub> technique<sup>13</sup> was employed for oxygen extraction from the quartz samples. D/H ratios were measured on fluid inclusion waters extracted from quartz by thermal decrepitation, the released water being reacted with uranium metal at 750°C. Mine water samples were also reacted with uranium metal at 750°C to produce hydrogen gas. The mass spectrometric results are presented in the standard δ-notation. Analytical reproducibilities were ±0.1‰ for oxygen and ±3.0‰ for hydrogen from fluid inclusion waters. All results are expressed with respect to SMOW.

#### Results

The oxygen and hydrogen isotope results are presented in Table 2. The δ<sup>18</sup>O values of the quartz samples vary from +0.15 to +1.78‰. The δD values of fluid inclusion waters vary from -125 to -134‰. The δD values of the present-day

mine waters vary from -128 to -141‰. The δ<sup>18</sup>O value of the hydrothermal fluids was calculated by use of the equation<sup>14</sup>

$$1000 \ln \alpha (Q - W) = 3.57 \times \left( \frac{10^6}{T^2} \right) - 2.73$$

where α is fractionation factor, Q and W are δ<sup>18</sup>O values of quartz and water, respectively, and T is temperature, K. The temperatures used in the calculations were determined from fluid inclusions. The calculated oxygen isotope values of the hydrothermal fluids, which are presented in Table 2, were found to vary from -6.8 to -8.8‰.

#### Comparison with other systems

A considerable quantity of fluid inclusion and stable isotope data is available for the epithermal gold deposits of the southwestern U.S.A., Mexico and other parts of the world. In the majority of these deposits circulating meteoric water has clearly been the dominant source of the mineralizing fluids, with apparently little or no fluid contribution from any magmatic source.<sup>15-21</sup> The δD values of the ore fluids are

Source of Au?

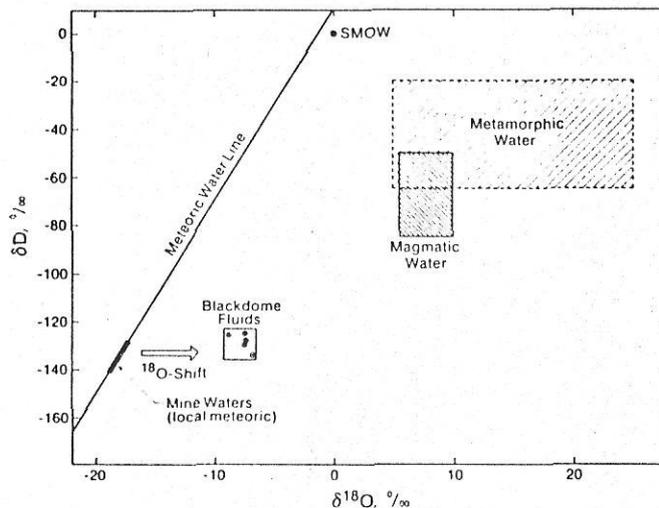


Fig. 5 Ore fluids from Blackdome Ag-Au deposit: plot of δD versus δ<sup>18</sup>O values

Table 2 Stable isotope data for quartz and hydrothermal fluids in Blackdome Au-Ag deposit, ‰ (SMOW)

Sample no.	Location	Mineral or sample	δ <sup>18</sup> O of quartz	δD of fluid inclusions	Calculated δ <sup>18</sup> O of hydrothermal fluids*
DDH/01	16.3 m	Massive, crystalline quartz	0.15	-126	-8.8
DDH/23	21.9 m	Massive, crystalline and euhedral quartz	0.91	-130	-7.5
DDH/08	31.8 m	Euhedral quartz	1.10	-125	-7.5
DDH/129	125.3 m	Massive, crystalline quartz	1.17	-128	-7.4
DDH/148	164.7 m	Large euhedral quartz	0.94	—	—
12120	(Drift at 1960-ft elevation)	Coarse, crystalline quartz	1.78	-134	-6.8
2	}	Mine waters	—	-132	—
4			—	-138	—
5			—	-140	—
7			—	-141	—
10			—	-128	—

\*Calculated from δ<sup>18</sup>O values of quartz and from temperatures determined from fluid inclusions.

normally found to be similar to the  $\delta D$  values of local meteoric waters, but the oxygen isotope: the ore fluids are commonly seen to have been exchanged by various degrees of reaction with the volcanic country rocks of the vein systems.<sup>22</sup>

Much the same is shown to be true of the Blackdome ore fluids. The  $\delta D$  values of fluid inclusion waters and mine waters and the calculated  $\delta^{18}O$  values of the ore fluids are plotted in Fig. 5. The  $\delta D$  values of the fluid inclusion waters demonstrate a slight enrichment in D by comparison with  $\delta D$  values for the present-day meteoric water of the region, which suggests that the isotopic composition of Tertiary meteoric water did not deviate much from that of the present-day meteoric water. As in other epithermal deposits, however, a strong shift in  $\delta^{18}O$  is observed in the Blackdome ore fluids, which is obviously due to isotopic exchange between the thermal waters and the country rocks.

## Conclusions

A class of epithermal precious-metal deposits known as the adularia-sericite-type deposits was distinguished by Hayba *et al.*,<sup>23</sup> who defined it as being characterized by the following features.

- (1) Deposits of this type were generated in hydrothermal systems analogous to the present-day Taupo volcanic zone of New Zealand and the Yellowstone caldera of the U.S.A.
- (2) The metalliferous ores were deposited by a deeply circulating, partly boiling brine 'plume' at or close to its interface with a zone of meteoric recharge. The fluids of the system were buffered to a near-neutral pH and had their redox and sulphidization states buffered by Fe phases in the wallrocks and veins.
- (3) The acidity required to generate sericite alteration was provided by the condensation of acid volatiles in the upper reaches of the geothermal system.
- (4) The deposits are generally hosted by the volcanic components of suites of rhyolitic to andesitic volcanic and volcanoclastic-sedimentary rocks.
- (5) They characteristically carry acanthite, native gold, native silver, electrum and some base-metal sulphides and selenides. High Ag/Au ratios are common. Chlorite is a common gangue mineral, and many of the deposits have Mn-bearing gangue minerals.
- (6) The characteristic wallrock alteration is sericitic to argillic (with occasional kaolinite) and is associated with the development of abundant adularia; the sericitic alteration is characterized by the predominance of illite over smectites and mixed-layer clays.
- (7) Most ore deposition seems to have taken place at 250–300°C, whereas late-stage gangues exhibit lower formation temperatures of 140–200°C. Fluid salinities are generally low (< 3 wt% NaCl equivalent), though some have salinities of up to 12 wt% NaCl equivalent.
- (8) Most of the systems appear to register palaeodepths of 300–600 m, although some were operative at 1–1.4 km.
- (9) The hydrothermal systems appear to be dominated by meteoric components, though the magmatic contribution might attain 10%.

The same authors also stated that this type of epithermal precious-metal deposit was distinct from a second major (but rarer) class of deposit—the acid-sulphate type.<sup>23</sup> The latter class, which is associated with rhyodacitic, rhyolitic and trachyandesitic centres, was distinguished primarily on the basis of its alteration suite of advanced argillic to argillic  $\pm$  sericitic facies, commonly in association with alunite. The argillic alteration suites are typically kaolinite-rich. No adularia is found in this class of deposit, and chlorite is rare. The acid-sulphate type characteristically contains an associ-

ation of enargite-pyrite-gold-electrum and base-metal sulphides. So of this class contain bismuthinite, but none carries selenide.

It is clear, therefore, that the Blackdome deposits belong to the adularia-sericite class of Hayba *et al.*<sup>23</sup> in that virtually all of the characteristics of the Blackdome system fit exactly those criteria listed above. However, the strikingly polymetallic nature of the ores—with sulphosalts, selenides, arsenides and base-metal sulphides—is noteworthy.

It is concluded that the adularia-sericite-type polymetallic deposits of the Blackdome epithermal field were generated when Tertiary meteoric groundwaters penetrated tensional fracture systems in a cooling, calc-alkalic, emergent island-arc environment. The resulting geothermal field was probably underlain by a recirculating plume of brine that encountered meteoric waters at palaeodepths of 0.5–1.1 km. The precipitation deep within the cooling volcanic edifice of a wide range of elements leached by the brines was accompanied by extreme local phyllosilicate plus K-feldspar alteration and silicification of the walls of the geothermal reservoir. This hydrative metasomatism caused a positive exchange shift in the  $\delta^{18}O$  value of the fluids, away from the parent meteoric line. Occasional venting of the system (resulting in boiling) or selective hydrogen metasomatism of the wallrocks could have effected a minor positive shift in the  $\delta D$  value of the fluid. The metalliferous phases were probably precipitated during episodic boiling of the fluids.<sup>24,25</sup>

It is hoped that the data and observations presented here will serve to augment the sparse data on such systems and to assist in future in the early discriminatory analysis of potentially metalliferous systems in the Canadian Cordillera, as was recently advocated by Henley.<sup>21</sup>

## Acknowledgement

The study was made possible by the kind and generous cooperation of A. Reeve, Blackdome Exploration, Ltd. Dr. K. Muehlenbachs kindly provided the analytical facilities for the determination (by P. Maheux) of the oxygen isotope compositions of the quartz samples. Dr. R. W. Henley's erudite discourse at the Gold update '85–'86 symposium held at the University of Southampton in March, 1986, was a stimulating inspiration for the work presented here.

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