Depositional Setting of Silver-Rich Quartz-Sulphate-Carbonate Deposits of the Upper Kitsault River Area, Northwest British Columbia

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INTRODUCTION

The Upper Kitsault River area lies approximately 23 to 30 km north of Alice Arm, in the Skeena Mining Division, British Columbia. Mineral occurrences are of three principal types: copper and gold-rich quartz-chlorite stockwork deposits, silver-rich quartz-sulphate-carbonate deposits; and molybdenum-rich quartz stockwork deposits (Alldrick *et al.*, 1987). The first two types are hosted by lower Jurassic volcanic and sedimentary strata, near the top of the Hazelton volcanic arc sequence (Alldrick *et al.*, 1987; Godwin *et al.*, 1991). The third is considerably younger and is associated with a suite of Eocene quartz monzonite intrusions (Alldrick *et al.*, 1986).

There are conflicting opinions as to the origins of the silver-rich, quartz-sulphate-carbonate deposits. Originally, they were considered to be structurally-controlled "replacement" veins (Black, 1951; Campbell, 1959; Mitchell, 1973; Thompson and Michna, 1978). However, more recent work suggests that they may be exhalative in origin (Devlin and Godwin, 1986; Devlin, 1987). Pinsent (2001) discusses the previous work and provides descriptions of some of the more important occurrences in the upper Kitsault River area, and comments on similarities between the geological setting of the deposits and those at Eskay Creek (MINFILE 104B 008).

This report presents new fluid inclusion data from the past-producing silver-rich, quartz-sulphate-carbonate Torbrit (MINFILE 103P 191) and Dolly Varden (MINFILE 103P 188) deposits and the nearby Northstar (MINFILE 103P 189) and Wolf (MINFILE 103P 191) prospects (Figure 1). Fluid inclusions in quartz, sphalerite and barite from a variety of "grab-samples" of vein, breccia, disseminated, stringer and semi-massive styles of mineralization have been evaluated. Although the underground workings are no longer accessible and the precise location of only a few of the samples are known, temperature and composition data are used to establish the broad depositional environment of the deposits. The results are compared with published fluid inclusion data from volcanogenic massive sulphide, epithermal and hot-spring-type deposits, including the precious-metal rich Eskay Creek subaqueous hot-spring deposit.

GEOLOGICAL SETTING

The upper Kitsault River area is underlain by sedimentary and volcanic rocks of the upper Triassic Stuhini (Units 1 and 2; Figure 1) and lower Jurassic Hazelton (Units 3, 4 and 5; Figure 1) groups and sedimentary rocks of the lower-middle Jurassic Salmon River Formation (MacIntyre *et al.*, 1994; Alldrick *et al.,* 1986; Dawson and Alldrick, 1986). Open folds and faults affect the distribution of Hazelton Group andesitic pyroclastic and intercalated sedimentary rocks that host the silver-rich, quartz-sulphate-carbonate deposits (Dawson and Alldrick, 1986). The Dolly Varden, Northstar, Torbrit and Wolf deposits are in green and maroon andesites and related volcaniclastic sediments near the inferred top of the Hazelton volcanic arc. The rocks are disconformably overlain by fossiliferous sediments of the Salmon River Formation. The deposits are on the east side of a major northwesterly-trending, northerly plunging syncline. Dawson and Alldrick (1986) report that the entire Jurassic section in the Kitsault valley has undergone greenschist facies metamorphism. There are relatively few mapped intrusions in the Kitsault River area and virtually none in the vicinity of the deposits (cf., Figures 2 and 3, Pinsent, 2001; Devlin, 1987; Drown *et al.*, 1990).

SILVER-RICH QUARTZ-CARBONATE-SULPHATE DEPOSITS

Pinsent (2001) subdivides the silver-rich quartz-carbonate-sulphate and related deposits on the east side of the upper Kitsault River (Figure 1) into 3 types: 1) epigenetic silver-lead-zinc quartz-carbonate vein (*e.g.* Wolf); 2) syngenetic strontium-barium-lead-zinc-silver (*e.g.* Sault); and 3) epigenetic or syngenetic silver-lead-zinc-barium-strontium (*e.g.* Torbrit, Dolly Varden, Northstar) deposits.
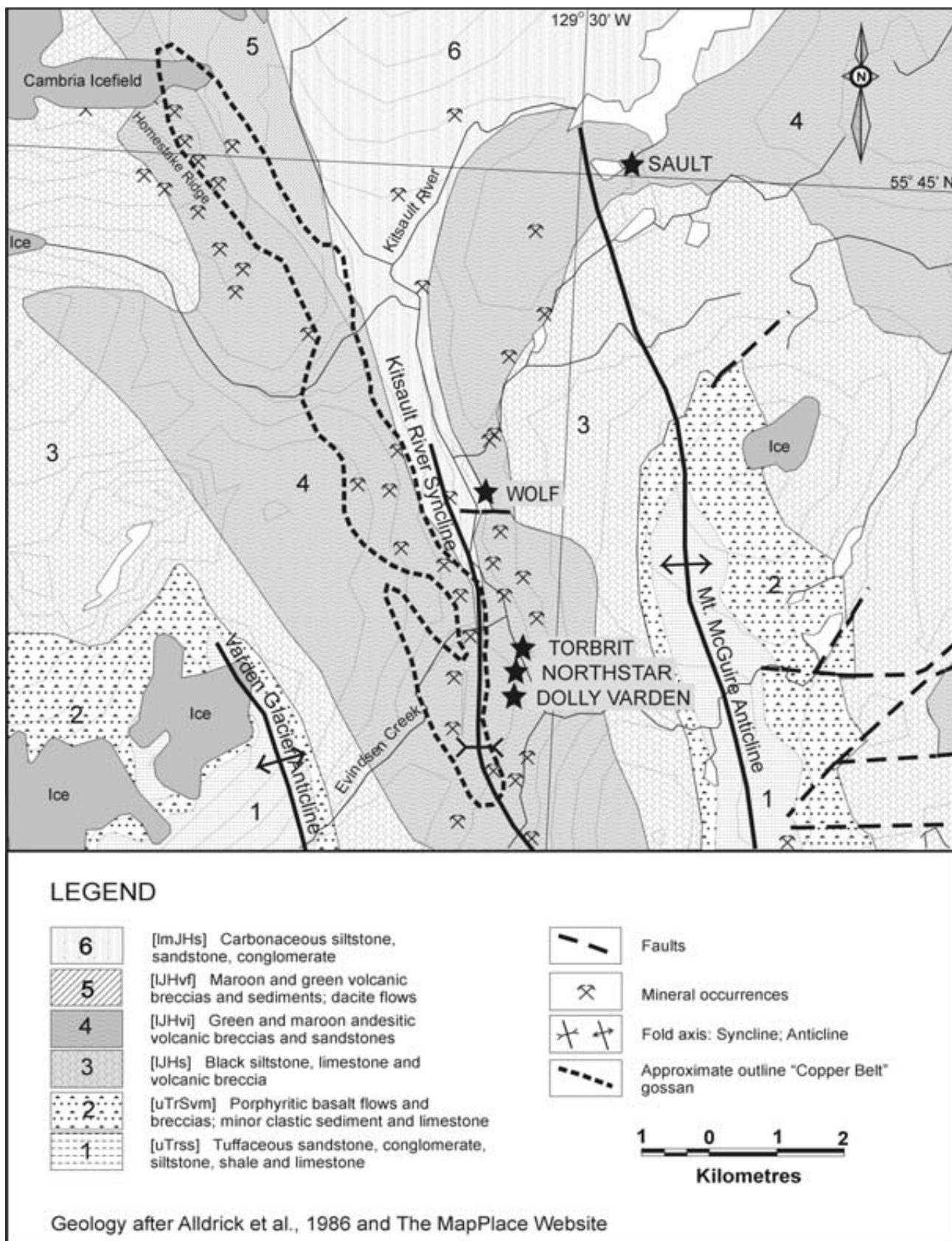
Figure 1. Generalized bedrock geology map of the upper Kitsault River area showing the location of deposits referred to in this study.

EPIGENETIC SILVER-LEAD-ZINC QUARTZ-CARBONATE

These deposits are described by Devlin (1987) and Thiersch (1986) as structurally controlled silver-base metal "replacement" veins that are not restricted to any specific rock unit but are most commonly found in permeable tuffaceous rocks. Devlin notes the presence of breccia and open-space textures, colloform bands of grey, white and jasperoid quartz, comb structures and well-terminated quartz crystals in occurrences of this type. Examples include the Wolf and less well documented David Copperfield, Mitchell, North Musketeer, Surprise and Tiger occurrences (Devlin, op. cit.). Carter (1964) and Thiersch (1986) describe the geology of the Wolf occurrence. The following description is summarized from the work of these authors.

WOLF

The Wolf occurrence comprises three quartz-carbonate "replacement" zones that include local concentrations of barite, jasper and sulphide. The zones may be fault off-set segments of a single discordant vein. The quartz-carbonate "replacement" zones are internally brecciated and bounded by hanging wall and footwall faults. Mineralization was multi-episodic and the vein is irregularly zoned. The following paragenetic sequence of hydrothermal events has been proposed. Early, vein quartz formed in open spaces with colloform banding, comb structures and well-terminated quartz crystals. Pyrite was also deposited with quartz in this open fluid system. The vein was then brecciated and fragments of quartz and pyrite were cemented by gangue, comprised of a second generation of pyrite, galena, sphalerite and minor calcite. After further brecciation, pyrite, galena, sphalerite, magnetite, hematite and unidentified silver-bearing minerals were deposited in small fractures in zones of fine-grained, crushed quartz, interstitial to the larger quartz fragments. The primary sulphide minerals have recrystallized; chalcopyrite has exsolved from sphalerite and pyrite has developed a framboidal texture. As a final mineralizing event, sphalerite and galena precipitated in a carbonate-rich gangue.

New petrographic work on four grab samples taken from the 340 Portal dump at the Wolf occurrence is in broad agreement with the proposed paragenesis. In addition, the following primary growth textures, characteristic of high-level epithermal or hot-spring type, deposits have been identified in early quartz: colloform (botryoidal) and crustiform (alternating) bands of chalcedony and comb quartz, moss-texture similar to that described by Dong *et al.* (1995) in which groups of spheres are highlighted by the distribution of impurities within silica minerals (Photo 1), and euhedral crystal growth zones defined by primary fluid inclusions (Photo 2). Colloform-textured bands of pyrite that probably formed with the quartz are seen in Photo 3.

Early-formed quartz exhibits a number of textures indicative of recrystallization and overprinting by a later metamorphic event. An early stage of this recrystallization is shown by crystals of feathery or flamboyant quartz simi-
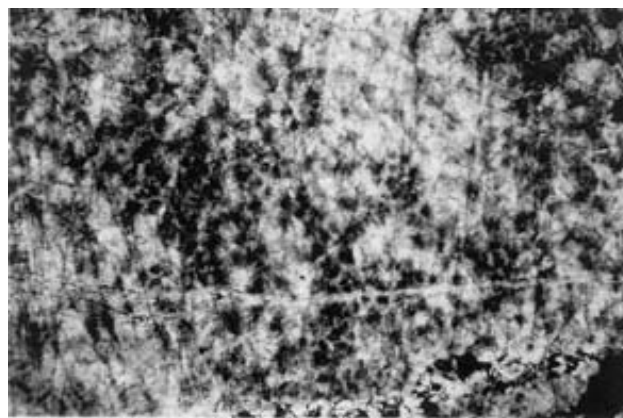

Photo 1. Moss-texture: groups of spheres highlighted by the distribution of impurities within silica minerals, Wolf deposit. Note that the original primary quartz texture is still preserved despite numerous cross-cutting microfractures. Sample RP-W-4. Transmitted plane light. Long field of view is 3.0 mm.
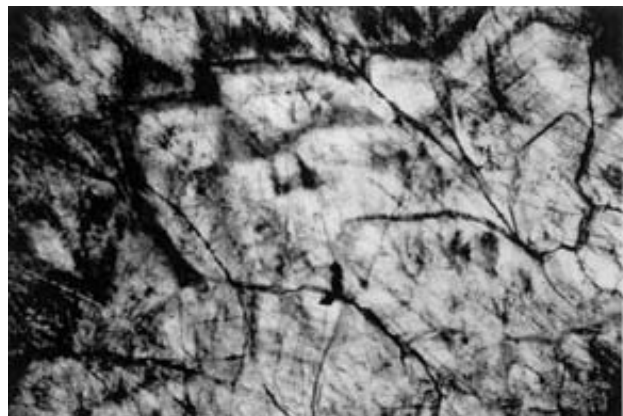

Photo 2. Euhedral quartz crystal growth zones defined by primary fluid inclusions, Wolf deposit. Sample RP-W-1. Transmitted plane light. Long field of view is 3.0 mm.
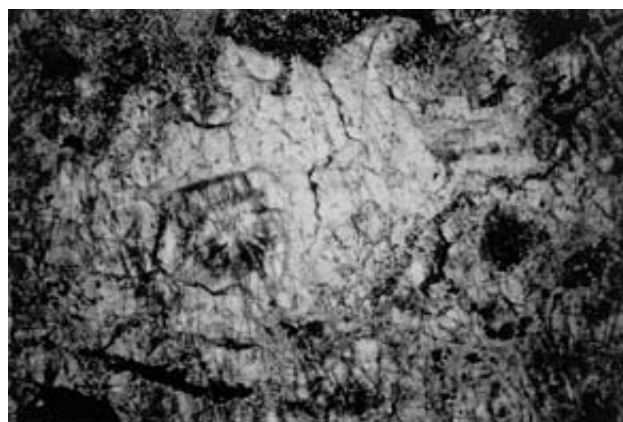

Photo 3. Colloform-textured pyrite with euhedral quartz, Wolf deposit. Note that the original primary growth zones are overprinted by fractures filled with secondary fluid inclusions. Sample RP-W-4. Transmitted plane light. Long field of view is 3.0 mm.

lar to those described by Dong *et al.* (1995). Elsewhere, original primary growth zones are overprinted by fractures filled with secondary fluid inclusions (Photos 1, 2, 3). The early quartz and its late overprinting are distinguished by different fluid inclusion compositions and homogenization temperature ranges (*see* below).

SYNGENETIC STRONTIUM-BARIUM-LEAD-ZINC-SILVER

Mineralization at the Sault (103P 233) occurrence is in a carbonate unit interbedded with andesite to rhyolite pyroclastic rocks just below a disconformity mapped at the top of the Hazelton volcanic arc (Pinsent, 2001). The carbonate unit is 8 metres thick, has been traced for approximately 5 kilometres along strike, and comprises a lower metalliferous carbonate diamictite, limestone and mudstone; a central volcaniclastic interval; and an upper sequence of laminated carbonate, sulphate and sulphide that contains a minor amount of tuff, chert and volcanic rock (Tupper and McCartney, 1990). The sulphide minerals include laminated to bedded and locally framboidal pyrite, fine-grained sphalerite and galena and locally well-bedded celestite (Pinsent, op. cit.).

A single sample of laminated carbonate and sulphate was examined but was found to be unsuitable for fluid inclusion work (Table 1).

EPIGENETIC OR SYNGENETIC SILVER-LEAD-ZINC-BARIUM-STRONTIUM

Mineralization at the Torbrit, Dolly Varden and Northstar deposits has been variously described as: 1) intrusion-related and epigenetic (Campbell, 1959); 2) a replacement vein disrupted by faulting and mineralized during a later epithermal event (Mitchell, 1973); and 3) fault offset segments of a single stratiform deposit (Devlin and Godwin, 1985; Devlin, 1987). They are classified as epigenetic or syngenetic silver-lead-zinc-barium-strontium deposits by Pinsent (2001) in recognition of the conflicting opinions as to their origins. Readers are referred to Black (1951) as well as the authors noted above for details on their geology, which are summarized only briefly below.

TORBRIT

The main deposit at Torbrit is a mineralized lens within an otherwise sub-economic sheeted silica, carbonate, sulphate and sulphide deposit in Hazelton Group volcanic rocks. Black (1951), Campbell (1959) and Mitchell (1973) considered that it formed through hydrothermal replacement of brecciated volcanic rock in a tensional fault system.

Devlin and Godwin (1985) and Devlin (1987) note that the deposit is stratabound and formed at a distinctive horizon within a thick succession of shallow-water Hazelton Group volcanic and related volcaniclastic rocks. They suggest that it may be exhalative in origin and that the Torbrit, Dolly Varden and Northstar deposits may have been part of a single, variable facies, stratabound mineral occurrence.

The unit shows gradation from silica-sulphide exhalite at the Dolly Varden East and Northstar deposits to carbonate-sulphate-sulphide exhalite at the Dolly Varden West and Northstar deposits and to sulphate-oxide-sulphide exhalite at Torbrit (Devlin, 1987).

The "vein" or "sulphate-oxide-sulphide exhalite" horizon at Torbrit is composed of quartz, jasper, chalcedony, barite and carbonate and the economically significant portion of the horizon includes up to 20% sulphide and oxide minerals (magnetite, hematite, pyrite, sphalerite, galena, chalcopyrite, tetrahedrite, pyrargyrite and trace native silver) (Campbell, 1959; Devlin, 1987). The gangue minerals are compositionally and colour-banded, commonly subparallel to deposit contacts and to the schistocity of the surrounding rock (Campbell, op. cit.). Campbell describes gangue minerals containing vugs lined with well-terminated quartz crystals and the occurrence of barite with a characteristic crustiform texture. He estimated a temperature of 270 °C for the formation of sphalerite by plotting the FeS content of the sphalerite on a portion of the system ZnS-FeS-S, and by employing the argentite-silver assemblage as a sulphur barometer (Devlin, 1987).

Fluid inclusion petrography was undertaken on transparent minerals in three samples from Torbrit (Table 1). Sample RP-T-1 is from a drill hole collared northwest of the Torbrit glory hole (McGuigan and Melnyk, 1991). It comprises light-grey subrounded fragments of silicified and sericitized quartz, from 0.1 to 0.5 mm in maximum dimension, infilled by pyrite and pale-green sphalerite. McGuigan and Melnyk (1991) report both honey and blackjack varies of sphalerite in this interval of core. Samples RP-T-2 and RP-T-3 are from the UBC Department of Earth and Ocean Sciences Museum Collection. Sample RP-T-2 comprises primary bladed barite (the bladed texture is common in epithermal deposits) with laths up to 1 cm in length, jasper-sulphides-oxides and colloform quartz. Sample RP-T-3 is similar to RP-T-1; it comprises subrounded fragments of silicified and sericitized (?) quartz infilled by disseminated and stringer sulphides, including pale-green sphalerite, which are cut by later barite and carbonate. Solid inclusions of reddish-brown sphalerite (?) occur along primary growth zones in the pale-green sphalerite (Photo 4).

DOLLY VARDEN

The Dolly Varden mine has been described as a series of ore-shoots within a single "replacement vein" in a package of massive, altered and pyritic volcanic breccias and sandstones (Black, 1951). Similar to Torbrit, the deposit is compositionally and colour-banded; it also contains fragments of locally derived wallrock (Black, 1951). Mitchell (1973) considered the Dolly Varden deposit to be an off-set portion of the same vein that formed the nearby Torbrit and Northstar deposits.

Devlin and Godwin (1986) divide the deposit into East and West segments. The mineralogy of the Dolly Varden East deposit consists of disseminated to massive pyrite, minor chalcopyrite and traces of argentite, pyrargyrite and native silver in a gangue of quartz and sericite and is referred to as a "silica-sulphide exhalite facies" by Devlin (1987). The

TABLE 1
DESCRIPTION OF SAMPLES USED FOR PETROGRAPHIC AND
MICROTHERMOMETRIC ANALYSES

DEPOSIT NAME	SAMPLE NUMBER	SAMPLE TYPE [1]	USE [2]	LOCATION DESCRIPTION	MINERALS EVALUATED [3]	MINERAL ASSOCIATION	SOME MINERAL TEXTURES
Wolf	RP-W-1	Grab	P/M	340 Portal Dump #1	quartz*	silica-sulphide	colloform (botryoidal) and crustiform (alternating) bands of quartz
	RP-W-2	Grab	P/M	340 Portal Dump #2	quartz* carbonate	silica-sulphide	colloform and crustiform textures, jasper
	RP-W-3	Grab	P/M	340 Portal Dump #3	quartz*	silica-sulphide	veinlet with well-terminated quartz crystals
	RP-W-4	Grab	P	340 Portal Dump #4	quartz	silica-sulphide	moss-textured quartz, framboidal pyrite
Sault	RP-K-1	Grab	P	Showing Lake	celestite? carbonate	carbonate-sulphate-sulphide	banded ore cut by celestite?-carbonate veinlet
Torbrit	RP-T-1	Core	P/M	DDH 90-22 ~163m	quartz* sphalerite* carbonate barite	silica-sulphate-sulphide	breccia textures, disseminated sphalerite, late carbonate veinlet
	RP-T-2	Grab	P	UBC Collection E 073 001.008	barite quartz	sulphate-oxide-sulphide	bladed barite crystals; colloform and crustiform quartz
	RP-T-3	Grab	P/M	UBC Collection 804 LD 32-56	quartz* sphalerite* barite*	silica-sulphate-(oxide?)-sulphide	breccia textures; sphalerite stringers; late barite veinlet
Dolly Varden	RP-D-1	Grab	P	RP#1 - 152	barite sphalerite	sulphate-sulphide	massive to bladed barite; minor sphalerite
	RP-D-2	Grab	P	RP#2	barite quartz carbonate	carbonate-sulphate-sulphide	breccia textures; massive barite
	RP-D-3	Grab	P/M	RP#4 - No. 3 gloryhole	quartz* sphalerite	silica-sulphide	breccia textures; comb-crustiform-colloform textured quartz; green plus brown sphalerite
	RP-D-4	Grab	P	RP#2 452 stope 125' from surface	quartz sphalerite	silica-carbonate-sulphide	colliform and crustiform quartz, moss quartz
	RP-D-5	Grab	P/M	UBC Collection #3 No. 16 trench Cu ore	barite* quartz*	silica-carbonate-sulphate-sulphide	prismatic quartz fragments, tabular barite, breccia textures
	RP-D-6	Grab	P	UBC Collection #1 452 A stope 125' from surface	sphalerite quartz barite	silica-carbonate-sulphate-sulphide	semi-massive sphalerite; breccia textures
Northstar	RP-N-1	Core	P/M	NS89-3 958'	quartz* barite carbonate	silica-carbonate-sulphate-sulphide	breccia textures, fragments euhedral quartz
	RP-N-2	Core	P/M	NS89-3 967'	sphalerite* quartz* barite* carbonate	silica-carbonate-sulphate-sulphide	breccia textures; disseminated sphalerite
	RP-N-3	Core	P/M	NS89-3 988'	barite* quartz* sphalerite	silica-sulphate-sulphide	breccia textures, fragments of euhedral quartz; disseminated sphalerite; massive barite
	RP-N-4	Grab	P	Northstar #1 Barytes NE Raise	barite quartz carbonate sphalerite	silica-carbonate-sulphate-sulphide	breccia textures, fragments of euhedral quartz; bladed barite; disseminated sphalerite

1. Sample Type: Core = split core sample; Grab = surface hand sample,
2. Use: P= fluid inclusion petrography, M = microthermometry,
3. Minerals evaluated with fluid inclusion transmitted light petrography: * = used for microthermometry

same author describes the Dolly Varden West deposit as a "carbonate-sulphate-sulphide" exhalite consisting of layers, disseminations and stringers of sphalerite and galena, minor pyrite, chalcopyrite and tetrahedrite, and traces of native silver in a gangue of calcite, quartz, siderite and barite. Exploration and drilling using the "exhalite" model led to the discovery of several zones of quartz-sulphide breccia composed of jasper, chalcedonic quartz and pyrite with trace amounts of economic sulphides (Drown *et al.*, 1990; McGuigan and Melnyk, 1991).

Petrographic work was undertaken on six grab samples from Dolly Varden taken from the UBC Department of Earth and Ocean Sciences Museum Collection (Table 1). Of particular interest are two samples (RP-D-3 collected from the No. 3 glory hole and sample RP-D-4 collected from the 452 stope at Dolly Varden East) which are breccias with fragments of early-formed comb, colloform and crustiform-textured quartz (Photo 5), moss-textured quartz and euhedral quartz with primary growth zones infilled by stringer and disseminated pyrite, galena and sphalerite. Sample RP-D-3 has two varieties of sphalerite: an earlier euhedral pale-green variety and later reddish-brown variety (equivalent to the honey and blackjack sphalerite described by McGuigan and Meinyk, 1991). Sample RP-D-1, collected from the 152 stope, comprises massive to bladed barite with minor sulphide stringers and trace sphalerite. Sample RP-D-5 (No. 16 trench - Cu ore) is dominantly altered wallrock with a few anhedral fragments of early-formed quartz that exhibits primary growth zones. The rock is infilled by disseminated and stringer sulphides and cut by subsequent late, one-millimetre wide, barite veinlets.

NORTHSTAR

The Northstar occurrence is described as a high-grade lens in a replacement "vein" in Hazelton Group volcanic rocks (Black, 1951; Mitchell, 1973). The deposit comprises barite and quartz with minor amounts of sulphide and sulphosalt minerals (pyrite, marcasite, galena, sphalerite, chalcopyrite, pyrargarite and argentite) and native silver (Pinsent, 2001). Banded and crustiform textures have been described, similar to those reported at the Torbrit mine (Black, 1951).

Alternatively, Devlin (1987) proposed that the Northstar deposit is exhalative in origin. He suggests that mineralized horizon may be stratigraphically zoned from a pyritic basal barite-quartz-carbonate unit upward into a more siliceous and metal-enriched, polymetallic sulphide-bearing unit. Drilling in 1990 based on this model intersected the mineralized horizon and a thick chlorite-calcite-pyrite alteration stockwork in its footwall down-dip of the main adit (Drown *et al.*, 1990). The "exhalite" comprised a lower carbonate-rich barren facies and upper weakly mineralized sulphide and oxide-bearing facies containing pyrite, chalcopyrite, honey-coloured sphalerite, galena and jasper (Drown *et al.*, 1990; McGuigan and Melnyk, 1991).

Fluid inclusion petrography was undertaken on four samples from the Northstar deposit (taken from drill core and the UBC Department of Earth and Ocean Sciences Mu-

Photo 4. Solid inclusions of reddish-brown sphalerite? with liquid-rich and vapour-rich? fluid inclusions which define primary growth zones in pale-green sphalerite, Torbrit deposit. Sample RP-T-3. Transmitted plane light. Long field of view is 200 µm.
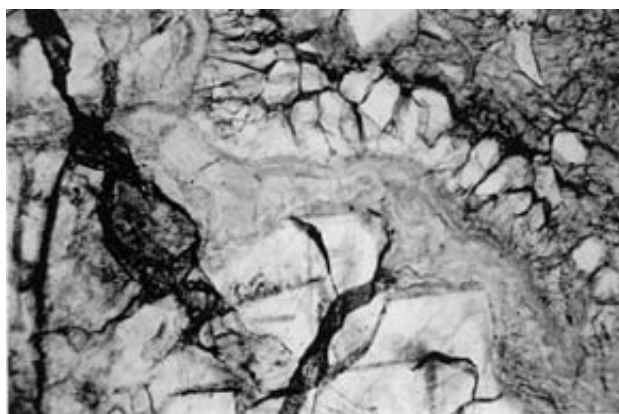

Photo 5. Fragment of early-formed comb, colloform and crustiform-textured quartz, Dolly Varden deposit. Sample RP-D-3. Transmitted plane light. Long field of view is 3.0 mm.

seum Collection, Table 1). Sample RP-N-1 is a breccia with angular fragments of quartz with primary growth zones; late white carbonate and barite form infill-textures with disseminated and stringer pyrite. Sample RP-N-2 is a similar breccia with fragments of quartz that display primary growth zones (Photo 6). Pale-green sphalerite occurs as disseminations and blebs. Barite and minor carbonate cut the mineralization. This sample came from an interval referred to by Drown *et al.* (1990) as being a "quartz breccia exhalite". Sample RP-N-3 is dominantly massive barite with fragments of euhedral quartz exhibiting primary growth zones; sulphides occur as trace disseminations of pyrite, chalcopyrite and reddish-brown sphalerite. This sample came from an interval of core Drown *et al.* (1990) referred to as "exhalative barite". Sample RP-N-4 is similar to RP-N-3, except that the barite is bladed.

FLUID INCLUSION DATA

Fluid inclusion work has concentrated on quartz from the "epigenetic silver-lead-zinc quartz-carbonate vein" at the Wolf prospect and on quartz, sphalerite and barite from

Photo 6. Fragment of early-formed vein quartz with euhedral crystals and primary growth zones, Northstar deposit. Sample RP-N-2. Transmitted plane light. Long field of view is 3.0 mm.

the "epigenetic or syngenetic silver-lead-zinc-barium-strontium deposits" at the former Torbrit and Dolly Varden silver mines and the related Northstar occurrence (Table 1). The temperature and composition of the hydrothermal fluids present during mineralization have been determined using conventional microthermometric work.

Eighteen 'quick plates' and doubly-polished sections were prepared for fluid inclusion petrography. Quick plates are sections, 80 to 100 microns thick, mounted on glass slides with epoxy and polished on the top surface only. Of these, 10 samples were found to be suitable for microthermometry and were re-prepared, where necessary, as doubly-polished sections. Samples were selected to give broad representation of silica, carbonate, sulphate, oxide and sulphide mineral associations (Table 1).

Quartz and sphalerite were used for the microthermometry because of their high tensile strength and relative translucency. Sphalerite is particularly useful as the microthermometric results can be directly tied to the paragenesis of the deposit. Barite is less useful as it is easily cleaved and highly susceptible to leakage and recrystallization of fluid inclusions (post-entrapment changes). Homogenization temperatures of fluid inclusions in barite were unusable because the inclusions had continued to heal at low temperatures after nucleation of a vapour phase (*i.e.* necked-down; *see* petrography below). The salinity measurements from fluid inclusions in barite were found to be usable.

Fluid inclusions were evaluated using the concept of fluid inclusion assemblages (FIA's). This ensures that the data are not biased by samples containing large numbers of fluid inclusions and helps to eliminate inconsistent results caused by changes in mass, volume or shape of inclusions after entrapment (*i.e.* eliminate non-representative inclusions that are the result of diffusion, stretching, or necking-down processes). A fluid inclusion assemblage (FIA) is a petrographically-associated group of inclusions such as those aligned along primary growth zones or secondary fracture planes. One representative data point, rather than several data points, is used for each FIA.

PETROGRAPHY

Fluid inclusions in quartz, sphalerite and barite in our samples are typically less than 10 microns and rarely reach a maximum of 30 microns in longest dimension. The fluid inclusions vary in shape from irregular to smooth and in some cases they mimic host crystal form and are 'negative-crystal'-shaped.

Fluid inclusions were classified as primary, secondary, pseudosecondary or indeterminate, based on the criteria of Roedder (1984) and Bodnar *et al.* (1985). Primary fluid inclusions were aligned along growth zones in quartz and sphalerite (Photos 6 and 7) and represent the fluid trapped while the host crystal was growing. Secondary inclusions were aligned along fractures that crosscut grain boundaries. Secondary fluid inclusion data represents post-entrapment fluid after primary crystal growth has ceased. Pseudosecondary fluid inclusions were aligned along fractures that do not crosscut grain boundaries and are presumed to represent fluids trapped in fractures at the time the crystal was growing. Fluid inclusions that occur in isolated clusters unrelated to fractures or growth zones were classified as indeterminate origin.

Primary fluid inclusions in quartz from all four deposits studied commonly contain two aqueous phases at room temperature, liquid (5 to 10 percent) and vapour (90 to 95 percent). This type of inclusion is referred to as two-phase aqueous liquid-rich (Type I) using the nomenclature of Nash (1976). Small (less than 5 microns) opaque fluid inclusions, which comprise about 10 percent of the total fluid population, are coeval with the Type I liquid-rich inclusions and aligned along growth zones. They may be vapour rich inclusions (Type II, using the nomenclature of Nash (1976)) that formed through the trapping of phase-separated volatiles. Alternatively, they may be air-filled voids or decrepitated inclusions caused by metamorphism.

Primary Type I fluid inclusions in sphalerite from the Torbrit mine comprise from 5 to 50 volume percent vapour. Opaque fluid inclusions, comprising 10 to 25 percent of the total fluid population, are coeval with the Type I liquid-rich
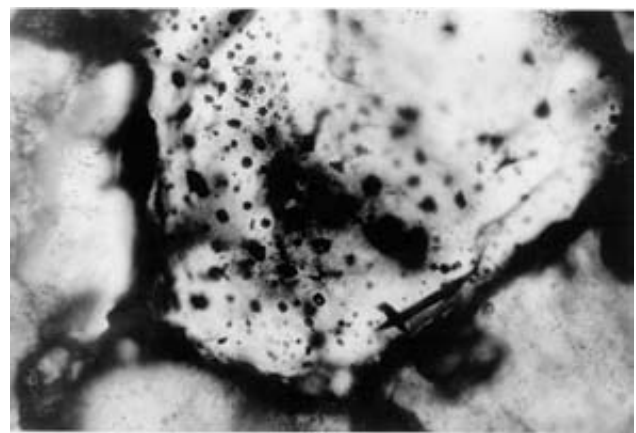

Photo 7. Pale-green sphalerite with primary growth zones defined by liquid-rich and vapour-rich fluid inclusions, Torbrit deposit. Sample RP-T-1. Transmitted plane light. Long field of view is 375 µm.
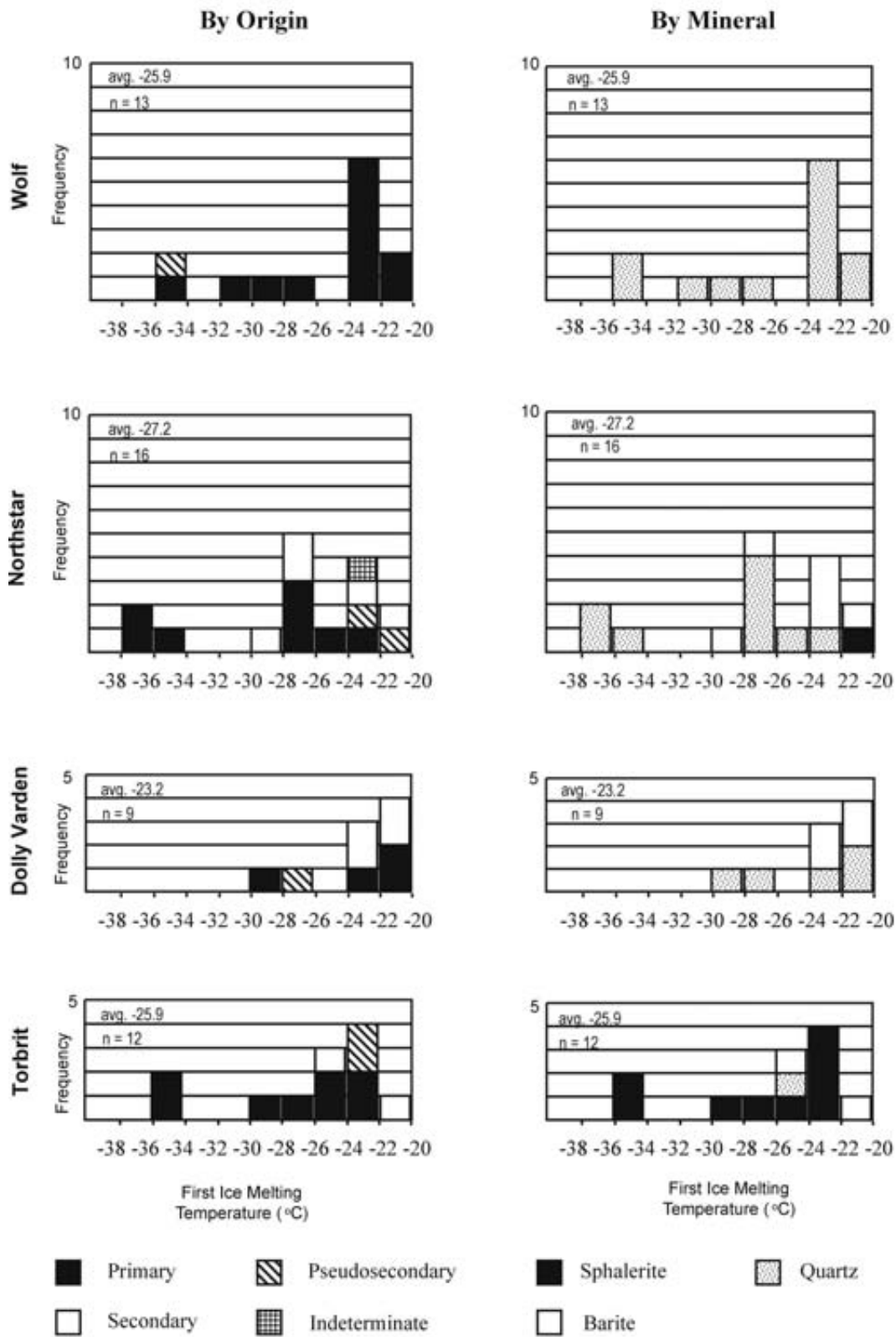
Figure 2. Temperatures of first melt of Type I (aqueous) fluid inclusions by fluid inclusion origin and by host mineral from the Wolf and Northstar occurrences and the former Dolly Varden and Torbrit mines, respectively. The first melt approximates the eutectic temperatures of the fluid inclusions.

inclusions and aligned along growth zones in the sphalerite (Photos 4 and 7). These opaque inclusions may be vapour rich inclusions (Type II), voids filled with air, or decrepitated fluid inclusions as suggested for quartz above.

Secondary multiphase (Type III) fluid inclusions have only been observed in quartz in sample RP-N-1 from the Northstar occurrence. These inclusions comprise liquid brine, vapour and one or more solid phases. The vapour phase typically comprises approximately 10 to 20 volume percent of the inclusion. Many of the solid phases are translucent and some appear to be cubic and are presumed to be salts. Confirmation of the identity of the solid phases as salts has not been possible as the fluid inclusions containing these phases decrepitate prior to solid phase dissolution. Since Type III inclusions typically occur with Type I and Type V (*see* below) fluid inclusions along healed fractures, it is possible that these Type III inclusions may have formed by accidental trapping of the solid phases or post-entrapment changes in the inclusions (necking-down).

Secondary two-phase and three-phase carbonic (CO_2-H_2O) type IV fluid inclusions have been observed healing fractures in quartz at the Wolf and Northstar occurrences. At room temperature (~20ºC), this type of fluid inclusion contains either two immiscible liquids: an outer aqueous liquid and inner CO_2-bearing liquid or two immiscible liquids and a vapour: an outer aqueous liquid, inner CO_2-bearing liquid and a CO_2-bearing vapour. The CO_2 volumetric proportions of Type IV inclusions range from 10 percent to 25 percent.

Very few secondary monophase vapour CO_2-CH_4 (Type V) fluid inclusions have been observed in quartz from the Wolf and Northstar occurrences. Type V inclusions are typically very dark and consist of a single vapour phase at room temperature. Freezing and subsequent melting behaviour of these inclusions indicate the presence of CO_2-CH_4±N_2 phases.

Two-phase liquid-rich Type IV inclusions are coeval with monophase vapour-rich Type V inclusions in secondary fracture planes in quartz in sample RP-W-1 at the Wolf occurrence. The coexistence of CO_2-bearing liquid-rich inclusions with variable liquid-to-vapour ratios and vapour-rich inclusions in the same fracture plane indicates that local effervescence may have occurred.

Secondary Type I fluid inclusions were observed in barite from the Dolly Varden and Torbrit mines and both secondary and primary Type I and Type II fluid inclusions were observed in barite at the Northstar occurrence. For the most part, the Type I barite inclusions are irregular-shaped, sometimes flat, and have inconsistent liquid to vapour ratios. The observation of monophase liquid-filled inclusions coexisting within individual fracture planes with these type I inclusions of variable liquid-to vapour ratio is evidence of post-entrapment changes such as necking-down (Bodnar *et al.*, 1985).

MICROTHERMOMETRIC DATA

Microthermometric data were obtained using a Fluid Inc. adapted USGS gas-flow heating-freezing stage housed at the Mineral Deposit Research Unit, Department of Earth and Ocean Sciences, University of British Columbia. Calibration of the stage was achieved using commercial Syn Flinc synthetic fluid inclusions and ice with the following accuracies: at -56.6±0.0ºC, 374.1±0.5ºC and 0.0±0.0ºC. Temperatures of phase changes are described below for each fluid inclusion assemblage, host mineral, fluid inclusion type, and origin. Variation in temperature and salinity between deposits with respect to fluid inclusion host mineral, origin, and fluid inclusion type are illustrated in Figures 2 though 5.

Type I Fluid Inclusions

Temperatures of first melting were obtained on 50 fluid inclusions from 10 samples representing mineralization at the Wolf, Northstar, Dolly Varden and Torbrit deposits (Figure 2). First melting temperatures for primary and pseudosecondary fluid inclusions range from about -37ºC to -19ºC at the Wolf, Northstar and Torbrit deposits and from -29ºC to -20ºC at the Dolly Varden deposit. These dissimilar ranges may reflect the relative paucity of data obtained from Dolly Varden rather than a truly systematic difference between deposits (Figure 2). The first melting temperature range of secondary fluid inclusions in barite is more restricted than the ranges for of quartz and sphalerite (Figure 2).

First melting temperature approximates the eutectic temperature of the salt-water mixtures. Depression of first melting below -21.2ºC, the stable NaCl-H_2O eutectic, indicates the addition of small concentrations of K^+, Ca^{2+}, Mg^{2+} or other ions to an H_2O-NaCl fluid. For the purposes of this study, the Type I fluid is modeled as an NaCl brine, partly because most formational fluids are NaCl-dominant (Goldstein and Reynolds, 1994) and because comparison of the cotectic surfaces where ice melts for various systems (Crawford, 1981, figure 6) shows only relatively small variations (< 5 wt.% change).

Final ice melting temperatures were obtained from 64 fluid inclusions from the same samples as the first melting temperatures (Figure 3). Final melting temperatures of primary fluid inclusions range from about -11ºC to -1.0ºC (average -3.8±2.9ºC) at the Northstar deposit but from only -5ºC to 0ºC (average -2.5 ±1.6ºC to -1.7±1.1ºC) at the Wolf, Dolly Varden and Torbrit deposits (Figure 3). Salinities for the Northstar deposit, calculated from final melting temperatures and the equation of Bodnar (1993), range from about 2 to 15 weight percent NaCl equivalent (wt. percent NaCl equiv.) and average 6.2± 3.6 wt. percent NaCl equiv. Salinities for the Wolf, Dolly Varden and Torbrit deposits are much lower, ranging from about 0.4 to 8 wt. percent NaCl equiv. and averaging 4.2±2.5, 4.0±3.6 and 2.9±1.8 wt. percent NaCl equiv. respectively. (Figure 3). The final melting temperature range of secondary fluid inclusions in barite and quartz is similar to that for primary fluid inclusions (-8.3ºC to -0.2ºC, Figure 3).

Final homogenization temperatures were obtained on Type I fluid inclusions in quartz and sphalerite from the same samples as the freezing data (above). Homogenization temperatures for primary fluid inclusions in sphalerite range

from 104.4 ºC to 352.8ºC and in quartz from 101.8 ºC to 266.4 ºC with significant variation between deposits (Figure 4). Temperatures above 270ºC were only recorded for Type I primary fluid inclusions in sphalerite from the Torbrit mine (Figure 4). Limited Type I primary fluid inclusion data recorded in quartz from the Dolly Varden mine are among the lowest, between 115ºC and 180ºC. Low to moderate-temperature (152ºC to 240ºC) secondary Type I fluid inclusions have only been reported in quartz (Figure 4).

Type II fluid inclusions

Microthermometric data could not be obtained from the primary opaque Type II fluid inclusions observed in quartz from the Wolf occurrence and in pale-green sphalerite at the Torbrit mine due to their opaque nature, and, in the case of the quartz, small size (<3 microns). However, inhomogeneous entrapment of liquid and vapour phases during boiling can be inferred by the coexistance of primary Type I fluid inclusions with variable liquid-to-vapour ratios (see petrography above) and coeval Type II fluid inclusions
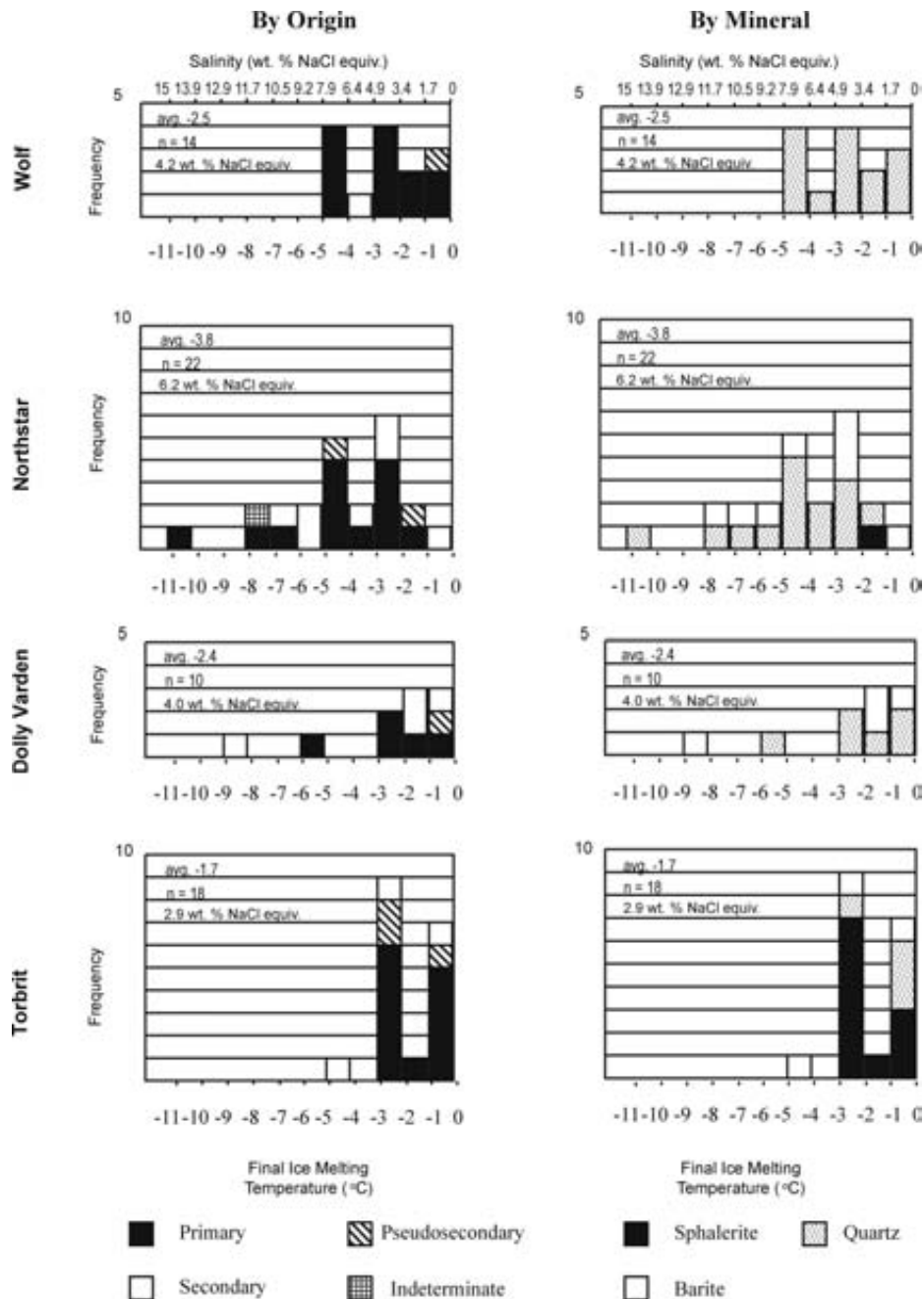

Figure 3. Temperatures of final melt of Type I (aqueous) fluid inclusions by fluid inclusion origin and by host mineral from the Wolf and Northstar occurrences and the former Dolly Varden and Torbrit mines, respectively. The final melt is used to calculate the equivalent salinity.

trapped in the same growth zones in the quartz and sphalerite. This inference is made with the assumption that the Type II fluid inclusions in these minerals are vapour-rich fluid inclusions. Secondary Type II inclusions in barite from the Northstar occurrence were not evaluated.

Type III Fluid Inclusions

Limited data (3 data points) on freezing and subsequent melting behaviours of secondary Type III fluid inclusions in quartz from the Northstar occurrence are different from the behaviour of Type I fluid inclusions (*see* Figures 2 and 3). First melting temperatures between -41°C and -28.4°C are significantly lower than those reported from Type I inclu-

sions (above) and may indicate the presence of salts such as CaCl$_2$ (Crawford, 1981; Davis *et al.*, 1990). Last melting temperatures recorded as -2.1°C and -2.8°C correspond to salinities of 3.6 and 4.7 wt. percent NaCl equiv.

Homogenization of Type III inclusions, in the presence of contained solid mineral phases, ranges from about 215°C to 247°C. On further heating, the fluid inclusions decrepitate at temperatures above 280°C prior to melting of contained solid phases. Given the limited data, it is difficult to evaluate whether the Type III inclusions contain minerals that are true 'daughter' minerals or if the minerals are trapped accidental solids or the result of 'necking-down'.
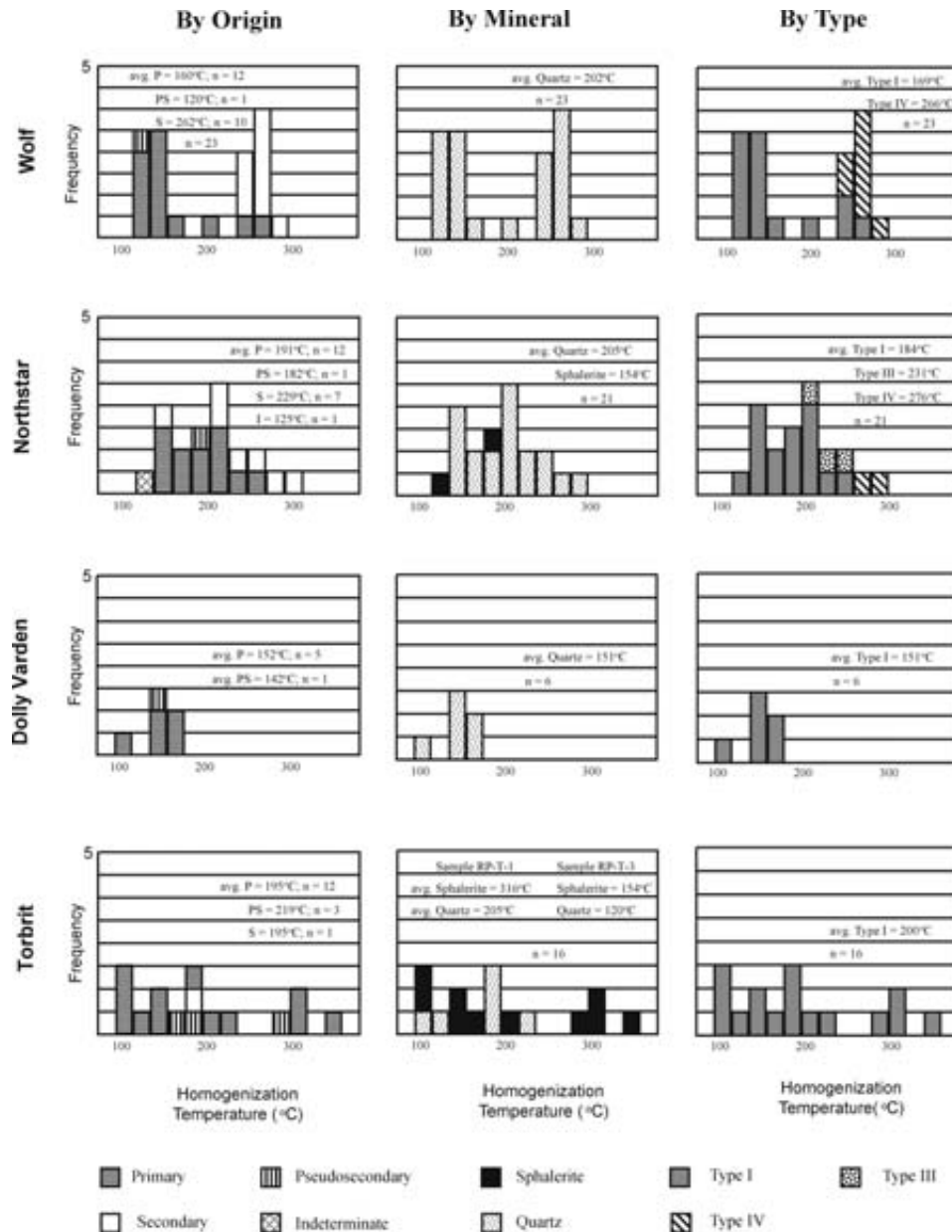

Figure 4. Final fluid inclusion homogenization temperatures (range, average and number), to the aqueous phase by fluid inclusion origin, host mineral and type from the Wolf and Northstar occurrences and the former Dolly Varden and Torbrit mines, respectively.

Type IV Fluid Inclusions

Secondary carbonic fluid inclusions were observed in quartz from the Wolf and Northstar deposits. Carbon dioxide melting temperatures of Type IV inclusions from the Northstar deposit are equivalent to the CO_2 triple point ($-56.6°C$). Melting temperatures of Type IV inclusions from the Wolf deposit range from -57.8 to $-56.6°C$ with an average of $-56.9\pm0.2°C$ (Figure 5). This average CO_2 melt temperature is very close to the CO_2 triple point of $-56.6°C$ which indicates that < 2 mole percent, using the method of Thiery *et al.* (1994), or virtually no CH_4 or N_2 are dissolved in the CO_2. Type IV fluid inclusions can therefore be modeled using an H_2O-CO_2-NaCl system.

Temperatures of clathrate (gas hydrate) melting were obtained on 10 fluid inclusions from the same samples as the CO_2-melting temperatures. Clathrate melting, which occurs after ice melting, varies from 3.7 to 8.2°C with an average of $6\pm1.5°C$ and 7.7 ± 0.7 °C for the Wolf and Northstar occurrences respectively (Figure 5). Clathrate melting temperatures less than +10°C are another indication of very low CH_4 or N_2 presence in Type IV inclusions. Clathrate melting temperatures in excess of + 10°C are related to CH_4 impurities (Burruss, 1981). Salinities calculated from clathrate melting, using the system H_2O-CO_2-NaCl and the computer program FLINCOR version 1.4 (Brown, 1989), range from 3 to 11.5 wt. percent NaCl equiv.

Homogenization temperatures of CO_2 liquid and vapour were obtained from 7 fluid inclusions from some of the same samples at the Wolf occurrence. Homogenization of the inclusions (always to the liquid phase) ranges from 19.9 to 27.5°C with an average of $24.4\pm1.9°C$ (Figure 5). The range in density, calculated as above (using

FLINCOR), is 0.67 to 0.75 grams per cubic centimetre for the CO_2 component of the inclusions.

Final homogenization temperatures of the inclusions, again always to the aqueous phase, were obtained from the same samples as the freezing data (above). Homogenization temperatures for secondary Type IV inclusions from both Wolf and Northstar occurrences are moderate ranging from 259.3 to 283.4°C (Figure 4). Figure 4 shows that overall, secondary Type IV fluid inclusions homogenize at significantly higher temperatures than Type I fluid inclusions for data evaluated in this study.

Type V Fluid Inclusions

Secondary Type V fluid inclusions were observed associated with Type III or Type IV fluid inclusions along fracture planes in two quartz samples from the Wolf and Northstar deposits. On freezing the monophase Type V inclusions, phase separation of the vapour bubble into CO_2-bearing liquid and CO_2-bearing vapour phases occurred at temperatures below 20°C. Further cooling resulted in freezing of the CO_2 phase at about -90 to -95°C. Carbon-dioxide melting temperatures are -56.8°C and -57.8°C; which are similar to the range observed for CO_2-melting of Type IV fluid inclusions (Figure 5). Homogenization temperatures of the inclusions to the liquid phase are 3.5 °C in the Northstar sample and 19.9 °C in the Wolf sample. The measured CO_2 melt and homogenization temperatures are used to calculate fluid molar volumes (or the density) and composition of Type V fluid inclusions using the VX diagrams of Thiery *et al.* (1994). The Type V inclusion from Wolf has a molar volume of 59 cubic centimetres per mol with 4 mole percent CH_4 dissolved in the CO_2. The Type V
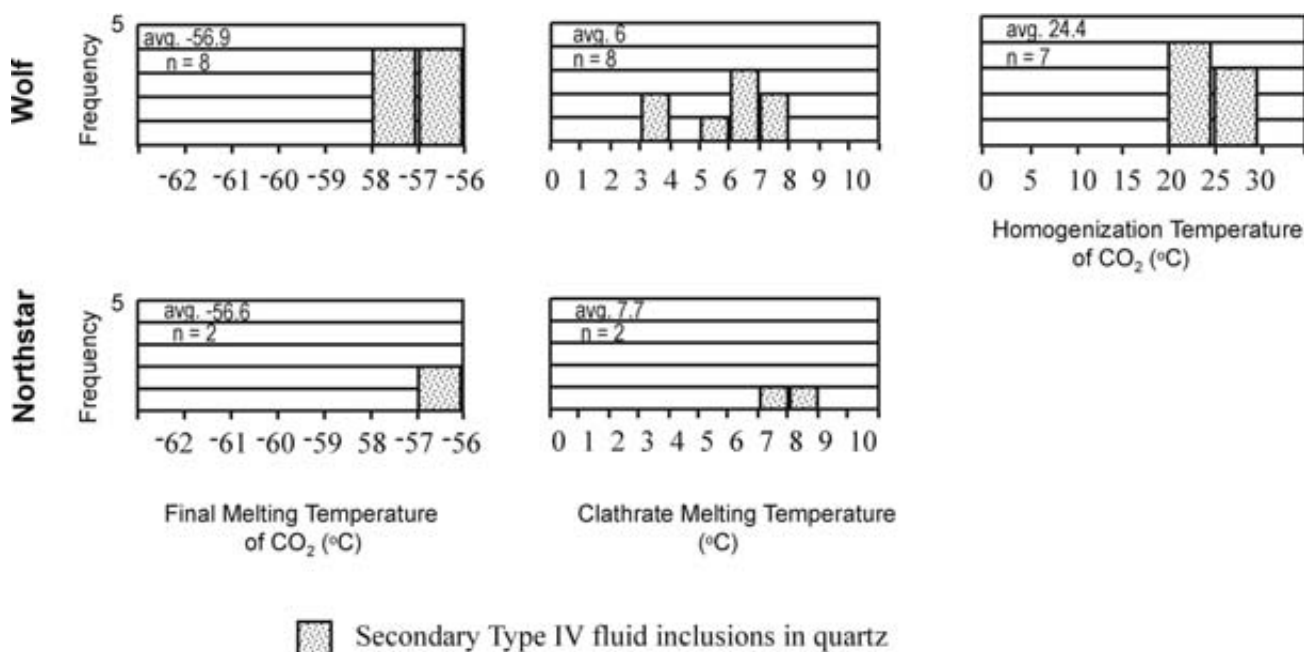

Figure 5. Temperatures of final CO_2 melt, clathrate melt and homogenization of CO_2 phases of secondary Type IV (CO_2-bearing) fluid inclusions in quartz from the Wolf and Northstar occurrences, respectively. The final CO_2 melt temperature is used approximate the proportion of CH_4, N_2 or other volatile phases trapped in the fluid inclusions. The clathrate melt is used to calculated the equivalent salinity. The homogenization temperature of CO_2 is used to calculate the CO_2 density.

inclusion from Northstar has a molar volume of 49 cubic centimetres per mol and 1 mole percent CH_4 dissolved in the CO_2 (Thiery *et al.*, op. cit.).

STABLE ISOTOPE DATA

Devlin (1987, pp. 86-90, table 4.2) reported temperatures of deposition from the former Dolly Varden and Torbrit mines and the Northstar and Wolf deposits as determined from pairs of sulphur and oxygen compounds using data calculated from sulphur and oxygen isotope fractionation equations. Devlin (1987) concluded that the range of realistic calculated temperatures for pairs of sulphur compounds from the Dolly Varden, Northstar and Torbrit deposits was between 143ºC and 375ºC. He noted that this range is consistent with exit temperatures measured in active hydrothermal vents on the East Pacific Rise, fluid inclusion temperatures determined for sulphide and sulphate minerals in Kuroko deposits and depositional temperatures calculated from sulphur isotope data for sphalerite-galena pairs from stratiform zinc-lead-barite deposits in Alaska. Realistic depositional temperatures for oxygen compounds from the Wolf and Dolly Varden deposits ranged from 152ºC to 190ºC (Devlin, op. cit.).

DISCUSSION

This discussion focuses on the following: (1) estimated fluid properties of inclusions in quartz and sphalerite from silver-rich quartz-carbonate-sulphate deposits in the upper Kitsault River area, (2) the relationship of fluid inclusions in host minerals to the introduction of metals in both epigenetic epithermal and syngenetic exhalative settings, and (3) proposed analogues to the silver-rich mineralization.

FLUID PROPERTIES

Fluid inclusion assemblages with liquid-rich aqueous (Type I) inclusions (relatively consistent liquid-to-vapour ratios) trapped with vapour-rich (Type II) inclusions in growth zones or fractures have been observed in many samples from silver-rich deposits in the upper Kitsault River area (*see* below). This fluid inclusion evidence for boiling is predicated on the assumption that the Type II inclusions do indeed contain a vapour phase and are not decrepitated, air-filled voids. Since microthermometric data could not be collected from the virtually opaque, often tiny Type II inclusions, fluid inclusion gas chromatographic analysis is required to validate this assumption.

Wolf

Primary Type I and Type II fluid inclusions occur in early, vein quartz that forms colloform banding, comb structures and well-terminated quartz crystals as a result of open-space filling. The Type I inclusions are low salinity (average 4.2 ± 2.5 wt % NaCl equiv., Figure 3) and homogenize at low temperatures (average 169±54ºC, Figure 4). These inclusions are similar in appearance to finely crystal-

line, irregular-shaped < 200ºC-type quartz that has been recognized in the subaerial epithermal environment (Bodnar *et al.*, 1985), but have higher average salinity (> 3.4 wt. % NaCl) which may indicate a submarine setting (see Hannington *et al.*, 1999, figure 15). Seawater is 3.1 wt. % NaCl equiv.

Evidence for boiling, given the assumption noted above, was recognized in one fluid inclusion assemblage (FIA) from sample RP-W-1. The estimated pressure of entrapment for fluid inclusions in this FIA, which homogenized at 138ºC, is 5 bars, using the equation of Brown and Lamb (1989) and the computer program FLINCOR (Brown, 1989). This equation and program are used throughout this paper for pressure estimates for Type I inclusions. A pressure of 5 bars indicates a near-surface sample depth of between 20 metres (assuming lithostatic load) and 50 metres (assuming hydrostatic load). At such shallow depths, pressure correction of homogenization temperatures for the remaining fluid inclusion assemblages are insignificant, even for unboiled fluids.

Further evidence to support depositional temperatures below 200 ºC is the stable isotope data of Devlin (1987, table 4.2). He reports calculated depositional temperatures of 152 ºC and 174 ºC for quartz-calcite and quartz-witherite pairs.

The low temperatures, salinities typically just above seawater, and calculated depths of formation reported for primary Type I fluid inclusions in early vein quartz at the Wolf occurrence are consistent with formation in a subaerial, or possibly submarine, hot-spring-type setting (Figure 6a).

Secondary high XH_2O (low XCO_2) Type IV (carbonic) fluid inclusions occur in numerous microfractures that cut the original low temperature quartz. These low-to-moderate salinity (average 7.4 ± 2.5 wt. % NaCl equiv.) CO_2-bearing inclusions were introduced at minimum (homogenization) temperatures of between 255 to 280 ºC and corresponding minimum pressures of between 1452 and 2776 bars using the equations of Brown and Lamb (1989) and the computer program FLINCOR (Brown, 1989). These pressures translate to minimum depths of formation of between 5.5 and 10.5 kilometres, assuming lithostatic load. Fluid inclusions of similar composition are found in low to medium grade metamorphic rocks and mesothermal to hypothermal ore deposits (Diamond, 1994).

Dolly Varden

Primary Type I and Type II fluid inclusions occur inside subangular breccia fragments of early-formed comb, colloform and crustiform-textured quartz, moss-textured quartz and euhedral quartz with primary growth zones. These fragments are infilled by stringer and disseminated pyrite, galena and sphalerite and veinlet-controlled barite. Sphalerite did not yield any usable inclusions for microthermometric study.

The Type I inclusions in quartz are low salinity (average 4.0 wt % NaCl equiv., Figure 3) and homogenize at low temperatures (average 151±27ºC, Figure 4). These inclu-

sions are finely crystalline and irregularly-shaped, similar to those described as < 200°C-type quartz at the Wolf (above). A lower salinity variety of this type of quartz has been recognized in the epithermal environment (Bodnar *et al.*, 1985). The average salinity of the inclusions in quartz from the Dolly Varden deposit may indicate a submarine setting (*see* Hannington *et al.*, 1999).

Evidence for boiling is reported from an FIA in sample RP-D-3. The estimated pressure of entrapment for fluid in-clusions in this FIA, which homogenized at 148°C, is 4 bars; which represents near-surface sample depths of between 15 metres (assuming lithostatic load) and 40 metres (assuming hydrostatic load).

Devlin (1987, Figure 4.2) reports calculated depositional temperatures, using sulphur and oxygen isotope data, of 190 °C for quartz-calcite and 192°C for barite-sphalerite pairs. These temperatures are slightly higher than our reported fluid inclusion range (Figure 4).
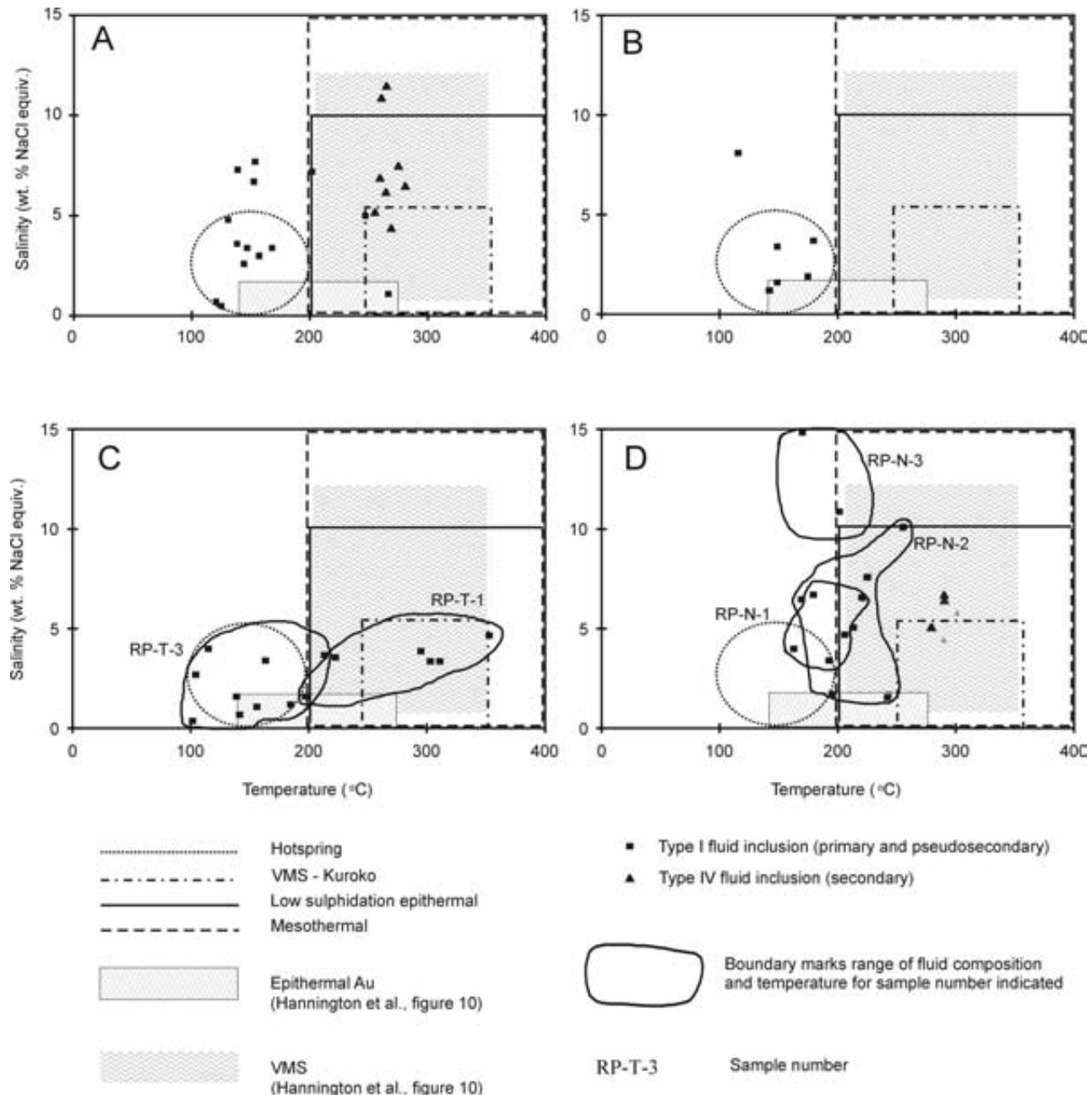

Figure 6. Salinity versus temperature for fluid inclusion assemblages at the a) Wolf occurrence, b) former Dolly Varden mine, c) former Torbrit mine, and d) Northstar occurrence. Groups of fluid inclusion assemblages (FIA's) from specific samples are circled. Boxes represent ranges of salinity and temperature from fluids in different ore deposit environments (after Reynolds, 1991; Dunne, 1992; and Lattanzi, 1991). Note that ranges for epithermal Au (stippled shading) and VMS (wavy-line shading) ore fluids (figure 10 of Hannington et al., 1999) differ from the above boxes.

Low temperatures, salinities near seawater composition and calculated depths of formation reported for primary Type I fluid inclusions in early vein quartz breccia fragments at the Dolly Varden deposit are similar to those observed at the Wolf occurrence, and are consistent with formation in a subaerial, or possibly submarine, hot-spring-type deposit (Figure 6b).

TORBRIT

Primary and pseudosecondary Type I fluid inclusions occur in subrounded to subangular, silicified and sericitized (?) quartz breccia fragments infilled by disseminated and stringer sulphides, including sphalerite. A small number of the finely-crystalline quartz fragments preserve primary growth zones. Primary and pseudosecondary Type I and Type II fluid inclusions occur in minor pale-green sphalerite associated with pyrite in core sample RP-T-1 and pale-green sphalerite associated with galena in grab sample RP-T-3. The final melting temperatures (salinities) of Type I primary and pseudosecondary fluid inclusions in quartz and in sphalerite cannot be distinguished (Figure 3). The salinities for these inclusions average 2.9±1.8 wt. % NaCl equiv. (Figure 3); similar to that of seawater.

Average homogenization temperatures for primary and pseudosecondary Type I fluid inclusions in early quartz fragments from samples RP-T-3 and RP-T-1 are $120 \pm 26\,^oC$ and $205 \pm 15\,^oC$ respectively (Figure 4). Average homogenization temperatures for Type I fluid inclusions, of similar origin, in pale-green sphalerite associated with pyrite in samples RP-T-1 and associated with galena in RP-T-3 are 316±26 ^oC and 154±38 ^oC respectively (Figure 4). Additional petrographic and fluid inclusion work on temporally and spatially constrained samples are required to resolve differences in temperature, and possibly composition, between the two apparently distinct populations of sphalerite present at the former Torbrit mine.

The low temperature fluid inclusions in finely-crystalline quartz with irregular shapes and somewhat inconsistent liquid-to-vapour ratios are similar to <200^oC -type quartz described from the epithermal environment (Bodnar *et al.*, 1985). The inclusions in quartz from Torbritt have average salinities that fall in the range of low temperature epithermal fluids (< 3.4 wt. % NaCl) and approximate seawater fluids (~ 3.1 eq. wt. % NaCl).

Evidence for boiling was not observed in the finely-crystalline quartz. Based on comparison of emplacement depths (~50 metres) in similar quartz observed at the Wolf and Dolly Varden deposits, it is likely that a maximum pressure correction of about 5^oC can be applied to homogenization data from fluid inclusions in quartz at Torbrit. Application of the maximum correction to homogenization temperatures of primary and pseudosecondary Type I inclusions in quartz yields trapping temperatures of approximately 125 ^oC (sample RP-T-3) and average trapping temperatures of 210±15^oC (sample RP-T-1).

Evidence for boiling can be seen in sphalerite from sample RP-T-3 from FIA 6-1. The estimated pressure of entrapment for fluid inclusions in this FIA that homogenize at 156^oC is 6 bars. This represents a near-surface sample depth of between 25 metres (assuming lithostatic load) and 60 metres (assuming hydrostatic load).

Evidence for boiling is reported in sphalerite from two FIA's in sample RP-T-1 that homogenize at 311.0 and 352.8^oC, respectively. The estimated pressure of entrapment for these FIA's are 97 and 163 bars which translates to moderate sample depths of between 370 and 620 metres (assuming lithostatic load) and 990 and 1660 metres (assuming hydrostatic load). Because the fluids are interpreted to have been boiling at the time of entrapment, no pressure corrections for conversion of homogenization temperature to trapping temperature for the remaining fluid inclusion assemblages in sphalerite were employed.

Further evidence to support both moderate and low depositional temperatures for sphalerite at Torbrit is from the stable isotope data of Devlin (1987, Table 4.2). He reports calculated depositional temperatures, using sulphur isotope data, of 346 ^oC and 405 ^oC for barite-sphalerite and 202^oC and 328^oC for sphalerite-galena pairs. Campbell (1959) estimated a moderate temperature of 270^oC for sphalerite formation at the Torbrit deposit using estimated FeS content and phase diagrams.

Low temperatures, salinities that range from nearly pure water to seawater composition (Figure 3), and textural similarities of primary and pseudosecondary Type I fluid inclusions in early vein quartz breccia fragments (sample RP-T-3) at the Torbrit deposit are similar to those observed at the Wolf and Dolly Varden deposits. The quartz breccia fragments and low temperature sphalerite from sample RP-T-3 are consistent with formation in a subaerial, or possibly submarine, hot-spring-type deposit (Figure 6c).

Fluid inclusions in quartz breccia fragments from sample RP-T-1 plot more within the lower temperature range of low sulphidation epithermal deposits or low-temperature subaqueous hydrothermal systems on Figure 6c. Homogenization temperatures for Type I fluid inclusions in sphalerite from RP-T-1 fall within the higher temperature range of low sulphidation epithermal deposits as well as within the range expected for modern black smokers and ancient volcanogenic massive sulphide deposits (Figure 6c).

Northstar

Fluid inclusion work at the Northstar occurrence was undertaken on three core samples from drill hole NS89-3 sampled at 958 feet (RP-N-1), 967 feet (RP-N-2) and 988 feet (RP-N-3). Primary Type I fluid inclusions occur in subangular to subrounded fragments of quartz vein (up to 5 millimetres) that appear to pre-date massive barite and disseminated and stringer sulphides, including sphalerite, as well as late barite and carbonate veinlets. The quartz vein fragments comprise typically euhedral, fine-to-medium grained quartz with well-preserved primary growth zones (Photo 6). Pseudosecondary and indeterminate Type I fluid inclusions occur in pale-green sphalerite associated with pyrite in sample RP-N-2. Microthermometric work on sphalerite from the Northstar is limited to this sample.

Final melting temperatures (salinities) of primary Type I fluid inclusions in the quartz from the drill core appear to vary with the down-hole depth of sampling. Salinities for primary Type I fluid inclusions in quartz from samples RP-N-1, RP-N-2 and RP-N-3 average 5.1±1.5 wt. % NaCl equiv., 6.2±3.1 wt. % NaCl equiv., and 12.9±2.4 wt. % NaCl equiv. (Figure 6d). These salinities are all significantly higher than average seawater. One measured salinity, from a pseudosecondary fluid inclusion in the sphalerite, was much lower at 1.7 wt. % NaCl equivalent.

Homogenization temperatures for both quartz and sphalerite are low (average 191± 30°C for quartz and 182 °C (n = 1) for sphalerite). The quartz is similar in appearance to finely crystalline, irregular-shaped < 200°C-type quartz with inconsistent liquid-to-vapour ratios and 200 °C to 230 °C -type quartz with consistent liquid-to-vapour ratios that forms in the epithermal environment (Bodnar *et al.*, 1985, Reynolds, 1991). Salinities typically less than 10 equiv. wt. % NaCl (Figure 3) are consistent with this interpretation. Low temperature fluids with similar salinities have also been reported in both quartz and sphalerite at Eskay Creek (Sherlock *et al.*, 1999, figures 7 and 8).

Evidence for boiling was not observed in quartz or sphalerite fluid inclusion assemblages from the Northstar occurrence. A confining pressure of about 21 bars is required to suppress phase separation (boiling) for the fluid that precipitated quartz at the maximum recorded homogenization temperature of 243°C (Figure 4) and salinities between 3 to 8 equiv. wt. % NaCl (Figure 3, equation of Bodnar and Vityk, 1994). Similarly, a confining pressure of about 7 bars is required to suppress boiling of the fluid that precipitated sphalerite at a temperature of 182°C and 1.7 eq. wt. % NaCl (equations of Bodnar and Vityk, op. cit.). Using these estimated pressures, the Northstar prospect formed under a water column of between 70 and 210 metres or at depths of 26 to 80 metres assuming a lithostatic pressure regime. The maximum pressure correction for a 210 metre water column overlying the mineralization is about 14°C (Potter, 1977). Application of this correction to homogenization temperatures of primary and pseudosecondary Type I inclusions yields trapping temperatures from 164 to 257°C.

Devlin (1987) reports calculated depositional temperatures, using sulphur isotope data, of 349 °C and 354 °C for barite-sphalerite pairs. Fluid inclusions with these moderate temperatures have not been observed in this study.

Pressure corrected homogenization temperatures from fluid inclusions in quartz vein fragments from samples RP-N-1 and RP-N-2 plot mostly within the lower temperature range of low sulphidation epithermal deposits or low-temperature subaqueous hydrothermal systems on Figure 6d. Fluid inclusions in sample RP-N-3 have much higher salinities.

Secondary Type IV (carbonic) and Type V (CO_2-CH_4) fluid inclusions occur in numerous microfractures that cut the original low temperature epithermal/low temperature subaqueous hydrothermal quartz in sample RP-N-1. The low salinity (average 5.9±1.2 wt. % NaCl equiv.) carbonic inclusions were introduced at minimum (homogenization) temperatures of between 268 °C to 283 °C, similar to temperatures recorded for secondary carbonic fluids at the Wolf occurrence (Figure 6a,d). In the absence of observed CO_2 liquid-vapour homogenization temperatures (due to the tiny size of Type IV fluid inclusions), minimum pressure estimates cannot be calculated. As discussed for the Wolf occurrence, carbonic fluid inclusions are found in low to medium grade metamorphic rocks and mesothermal to hypothermal ore deposits and may be a product of prograde metamorphism (Diamond, 1994, Marshall *et al.*, 2000). Secondary Type III (multiphase) fluid inclusions with low to moderate homogenization temperatures similar to those recorded in this study (sample RP-N-1) also can occur in metamorphosed and synmetamorphic ore deposits (Marshall *et al.*, op. cit.).

GENETIC MODELS/ANALOGUES

Although the metals present (barium, strontium, silver, lead and zinc) in the mineral deposits east of the Kitsault River are indicative of genetically related deposits (Thiersch, 1986; Devlin, 1987), there are differences in opinion as to the mode of origin of specific deposits. While most authors agree that the mineralization at Sault is syngenetic, and at Wolf is epigenetic, some consider the Dolly Varden, Torbrit and Northstar to be epigenetic "replacement" (Campbell, 1959; Black, 1951; Mitchell, 1973; Thiersch, 1986), and others consider them to be syngenetic (Devlin and Godwin, 1986; Devlin, 1987; Drown *et al.*, 1990; McGuigan and Melnyk, 1991, Tupper and McCartney, 1990).

EVIDENCE FOR HOT-SPRING-TYPE DEPOSITS

New fluid inclusion data from the Wolf, Dolly Varden, Torbrit and Northstar deposits indicates that the hydrothermal fluids responsible for deposition of early vein quartz and vein quartz breccia fragments at the Wolf, Dolly Varden and Torbrit deposits and disseminated sphalerite mineralization associated with galena at the Torbrit and pyrite at the Northstar deposits are low temperature (< 200°C) and low salinity (< 5 wt. % NaCl equivalent.), consistent with formation in either subaerial or near-surface subaqueous hot-spring-type deposits (Figure 6a,b,c,d). These data are supported by calculations of some low depositional temperatures (<~200°C) for sulphide-sulphate, sulphide-sulphide, silica-carbonate pairs at the Wolf, Dolly Varden and Torbrit deposits using sulphur and oxygen isotope data (Devlin, 1987, table 4.2). Similar low temperature and low salinity hydrothermal fluids are reported from fluid inclusions in quartz and sphalerite at the Eskay Creek deposit (Sherlock *et al.*, 1999).

Calculated fluid pressures are very low, about 5 bars, for primary fluid inclusions in early vein quartz and vein quartz breccia fragments at the Wolf and Dolly Varden deposits and from primary fluid inclusions in sphalerite at the Torbrit deposit that exhibit evidence for boiling. Note that evidence for boiling is inferred by the coexistence of primary Type I fluid inclusions with variable liquid-to-vapour ratios and coeval Type II fluid inclusions trapped in the same

growth zones in the quartz and sphalerite. This inference is made with the assumption that the Type II fluid inclusions in these minerals are true vapour-rich fluid inclusions and not air-filled voids. The calculated fluid pressure of 5 bars, assuming boiling fluids, equates to deposition at water depths of about 50 metres or 20 metres of overlying rock.

Examples of active shallow, submarine hot-spring deposits include low temperature pyritic sulphides forming from the Punta Banda hot-springs, California borderlands and related deposits, such as sulphide veins that occur in marine sediments (boiling vents) in Kagoshima Bay, S. Kyushu (Hannington *et al.*, 1999, Table 6). Both examples are forming at < 100 metre depths (Hannington, op. cit.). The Eskay Creek deposit, based on fluid inclusion data, is considered to have deposited from boiling fluids at fluid pressures of 150 bars and water depths of 1500 metres (Sherlock *et al.*, 1999). Interestingly, Sherlock *et al.* (1999) reports tiny, opaque inclusions coeval with Type I fluid inclusions that may be vapour-rich; microthermometric data was unobtainable from these opaque inclusions. Examples of subaerial epithermal hot-spring-type precious metal deposits formed at very shallow levels include Paradise Peak, Nevada (John *et al.*, 1991) and deposits in the Hart Mining District, California (Ausburn, 1991).

EVIDENCE FOR LOW SULPHIDATION EPITHERMAL/VMS DEPOSITS

Primary fluid inclusions in some vein quartz breccia fragments from the Torbrit and Northstar deposits are slightly higher temperature (200ºC to 230ºC), and in the case of the Northstar, higher salinity (>5 wt. % NaCl equiv.). The hydrothermal fluids responsible for initial deposition of these vein fragments formed in the lower temperature range of low sulphidation epithermal deposits or perhaps in the range of volcanogenic massive sulphide deposits as defined by Lattanzi (1991, figure 9).

Primary and pseudo secondary fluid inclusions in pale-green sphalerite associated with pyrite from the Torbrit are moderate temperature (295ºC to 350ºC) and low salinity (<5 wt. % NaCl eq.) consistent with formation in the higher temperature range of low sulphidation epithermal deposits as well as within the range expected for modern black smokers and ancient volcanogenic massive sulphide deposits (Figure 6c). These data are supported by calculations of moderate depositional temperatures (328ºC to 405ºC) for sulphide-sulphate and sulphide-sulphide pairs using sulphur isotope data (Devlin, 1987). Calculated fluid pressures from these moderate temperature fluid inclusions in sphalerite are 97 and 163 bars. These fluid pressures are typical for modern black smokers, ancient volcanogenic massive sulphide deposits and are within the range reported for the Eskay Creek deposit (150 bars, *see* above). The calculated fluid pressure equates to water depths of 970 and 1630 metres or relatively shallow rock sample depths of between 370 and 620 metres.

Devlin (1987) identified a distinctive, silica, carbonate, sulphate and sulphide-bearing horizon that can be traced for several kilometres along strike within a thick succession of shallow-water Hazelton Group volcanic and related volcano-sedimentary rocks. He considered this horizon to be exhalative in origin and host the Dolly Varden, Northstar and Torbrit deposits. He reconciles compositional differences within the horizon and differences between the three deposits by proposing that the 'facies' changes (silica-sulphide at Dolly Varden, carbonate-sulphate-sulphide at Northstar and sulphate-oxide-sulphate at Torbrit) are consistent with changing fluid chemistry brought about by mixing of exhalative fluids and sea water and differing depths of deposition. The Dolly Varden deposit is inferred to have formed under less oxidizing, deeper water conditions than the Torbrit (Devlin, 1987; Devlin and Godwin, 1986).

THE TRANSITIONAL EPITHERMAL-VMS GENETIC MODEL

Evidence of early, high-level deposition of silicates, sulphates and sulphides from low temperature, low salinity fluids is indicated by colloform, crustiform, comb, and locally bladed mineral textures and fluid inclusions in quartz, barite and sphalerite. These minerals may have deposited in veins, or possibly, in sea-floor mounds. Collapse and/or erosion of vein or mound material is indicated by local brecciation of this material. Alternatively, the breccia zones may have formed as a result of sealing and over-pressuring of the hydrothermal system followed by explosive brecciation. Later, local introduction of low to moderate temperature and low salinity fluids is indicated by infill textures of sulphides, sulphates and carbonate and fluid inclusions in sphalerite.

The Torbrit, Northstar and Dolly Varden deposits are perhaps best described as transitional epithermal-VMS deposits, a "polygot" category proposed by Galley (2001). He notes that this category of deposits "includes precious metal-rich VMS deposits that usually form within a shallow (<1 km) aqueous environment, are associated with felsic cryptodome complexes emplaced in a mixed volcaniclastic-siliciclastic succession overlying a rifted evolved arc sequence" (Galley, op. cit., p. 24). He suggests that deposits associated with extensive sericite-quartz-pyrite alteration, perhaps with associated Fe-carbonate and/or barite, and with sphalerite, galena and pyrite as common sulphide minerals are included in this category. He proposes that these are the base-metal-rich equivalent of submarine low sulphidation epithermal deposits (Sillitoe *et al.*, 1996). Examples of British Columbia deposits of this type are Eskay Creek (Roth *et al.*, 1999) and Rea Gold and Homestake (Hoy, 1991).

EVIDENCE FOR LATE METAMORPHIC (?) FLUIDS

Microfractures defined by secondary CO_2-bearing fluid inclusions overprint primary growth banding in quartz at the Wolf and Northstar deposits and indicate that both these deposits may have been subjected to a post-mineral (?) regionally extensive, metamorphic event. Abundant microfractures have also been observed in quartz at the Dolly Varden and Torbrit deposits. The composition of fluid inclusions in the microfractures from the latter two deposits

has not been evaluated. It is likely that all the silver-rich mineral deposits in the upper Kitsault River area have undergone regional metamorphism.

SUMMARY

This initial study of fluid inclusions in quartz, sphalerite and barite from the Wolf, Dolly Varden, Torbrit and Northstar deposits provides the following new information concerning the nature of fluids that relate to epigenetic Ag-Pb-Zn quartz-carbonate vein deposits and epigenetic or syngenetic Ag-Pb-Zn-Ba deposits in the upper Kitsault River area.

KEY OBSERVATIONS AND RESULTS

- Primary growth textures characteristic of high-level subaerial or submarine hot-spring type deposits have been identified in early quartz veins and vein quartz breccias at the Wolf and Dolly Varden deposits. These textures include: colloform (botryoidal) and crustiform (alternating) bands of chalcedony and finely-crystalline quartz, comb quartz, moss-textured quartz and euhedral crystals defined by primary growth zones.

- Quartz breccia fragments at the Torbrit and Northstar deposits are subangular to subrounded and comprise euhedral to anhedral, fine-to-medium grained quartz with well-preserved primary growth zones.

- The following five compositional types of fluid inclusions have been identified in quartz based on phases present at room temperature and microthermometric data: primary, pseudosecondary and secondary Type I: 'Aqueous' H_2O-NaCl, primary Type II: 'Vapour-rich' H_2O-NaCl, secondary Type III: 'Multiphase', secondary Type IV: 'CO_2-bearing or carbonic' H_2O-CO_2-NaCl and secondary Type V: 'CO_2-CH_4'. It is possible that the Type II fluid inclusions are air-filled voids; their opaque nature precludes microthermometric evaluation.

- Pseudosecondary and secondary Type I fluid inclusions have been identified in barite. Primary and pseudosecondary Type I and II fluid inclusions have been identified in sphalerite.

- Early vein quartz and vein quartz breccia fragments at the Wolf, Dolly Varden and Torbrit deposits contain fluid inclusions that are low temperature (<200°C) and low salinity (< 5 wt. % NaCl equiv.) consistent with formation in subaerial or near-surface submarine hot-spring-type deposits.

- Early vein quartz fragments at the Northstar deposits, and some from Torbrit, are slightly higher temperature (200 to 230°C) and in the case of the Northstar, higher salinity (> 5 wt. % NaCl equiv.) consistent with formation in low sulphidation epithermal deposits or perhaps in volcanogenic massive sulphide deposits.

- Two distinct populations of pale-green sphalerite from Torbrit are apparent, based on homogenization temperatures for primary fluid inclusions. Sphalerite associated with galena formed at low temperature (average 154±38°C) and low salinity (< 5 wt. % NaCl eq.) consistent with conditions for subaerial or submarine hot-spring-type deposits. Sphalerite associated with pyrite was deposited at moderate temperature (average 316± 26°C) and low salinity (< 5 wt. % NaCl eq.) consis-

tent with formation in the higher temperature range of low sulphidation epithermal deposits, modern black smokers and ancient volcanogenic massive sulphide deposits.

- Limited fluid inclusion data from pale-green sphalerite associated with pyrite at the Northstar occurrence indicates low temperature (125 and 182°C) and low salinity (1.7 wt. % NaCl eq.) fluids similar to the low temperature sphalerite variety at the Torbrit deposit.

- The occurrence of liquid-rich and probable vapour-rich fluid inclusions in the same primary growth zones provided evidence for boiling in some quartz samples from the Wolf and Dolly Varden deposits and in sphalerite from the Torbrit deposit.

- The following pressure estimates have been calculated using fluid inclusion data:

  Wolf: 5 bars (primary fluid inclusions in early vein quartz and quartz breccia fragments, evidence for boiling)

  Dolly Varden: 4 bars (primary fluid inclusions in early vein quartz and quartz breccia fragments, evidence for boiling)

  Torbrit(sample RP-T-3): 6 bars (primary and pseudosecondary fluid inclusions in sphalerite, evidence for boiling)

  Northstar (sample RP-N-2): 21 and 7 bars (primary fluid inclusions in early vein quartz and quartz breccia fragments and pseudosecondary fluid inclusions in sphalerite, minimum estimates - no evidence for boiling)

- Pressure estimates from early quartz and sphalerite from the Wolf, Dolly Varden, Torbrit (sample RP-T-3) and Northstar deposits equate to deposition at water depths of approximately 40 to 210 metres or rock depths of about 15 to 80 metres and are consistent with formation in a near-surface hot-spring-type depositional setting.

- Pressure estimates of 97 and 163 bars from primary and pseudosecondary fluid inclusions in sphalerite from the Torbrit deposit (sample RP-T-1) correspond to deposition from boiling fluids at significantly greater water depths of approximately 370 and 620 metres or greater rock depths of about 990 and 1660 metres.

- Secondary CO_2-bearing fluid inclusions define microfractures that overprint the primary growth textures in quartz at the Wolf and Northstar deposits and indicate that these deposits may have been subjected to a regional metamorphic event. The relatively low salinity, CO_2-bearing inclusions were introduced at minimum (homogenization) temperatures of between 255°C to 283°C and corresponding minimum pressures, for the Wolf deposit, of between 1452 and 2776 bars. These pressures translate to minimum depths of formation of between 5.5 and 10.5 kilometres for secondary, metamorphic (?) fluids at the Wolf deposit (assuming lithostatic load).

CONCLUSIONS

This fluid inclusion study, together with existing geological and geochemical data, supports the contention that the silver-rich deposits in the upper Kitsault River area are

genetically related. It also suggests that the deposits may be silver-rich analogues to the precious metal-rich Eskay Creek deposit. The Kitsault River deposits all formed at surface or at shallow depth in the waning stages of Hazelton arc volcanism. They have similar tenor (silver, lead, zinc, strontium, barium) and mineralogy. Their mineralization varies from multi-episodic and irregularly zoned to laminated and bedded, perhaps relating to proximity to subaqueous chimneys, surface mounds or collapse-textures in shallow marine basins or emplacement along active faults. Colloform, crustiform and comb textures clearly indicate early, high-level deposition of quartz in veins that formed from low temperature, and for the most part, low salinity hydrothermal fluids in a hot-spring-type setting. These early veins are locally brecciated, perhaps indicating near-contemporary structural activity or collapse. Alternatively, the brecciated zones may be the result of near-surface explosive brecciation. The silver was probably precipitated from low-to-moderate temperature and low salinity fluids that also deposited sphalerite and other sulphide minerals. It could either have been deposited in a subaerial hot-spring - low sulphidation epithermal environment or, possibly, a submarine hot-spring - volcanic-hosted massive sulphide-type depositional setting.

ACKNOWLEDGMENTS

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