Geology, Lithogeochemistry, and Alteration of the Battle Volcanogenic Massive Sulfide Zone, Buttle Lake Mining Camp, Vancouver Island, British Columbia

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Abstract

Volcanogenic, polymetallic massive sulfide deposits within the Buttle Lake mining camp occur within the felsic volcanic and volcaniclastic rocks of the Myra formation that immediately overlies Price formation andesite. These units comprise the lower exposed part of the Paleozoic Sicker Group in the Buttle Lake uplift in central Vancouver Island. The Sicker Group represents a volcanic island arc that forms the base of the allochthonous Wrangell terrane.

The Battle Main zone contains 2.3 million tons (Mt) of proven and probable reserves grading 1.3 g/t Au, 25.3 g/t Ag, 2.5 percent Cu, 0.5 percent Pb, and 13.2 percent Zn. Overall, the Buttle Lake camp hosts geologic reserves of about 12.5 Mt. The Battle Main massive sulfide zone occurs within the H-W horizon, the lowest member of the Myra formation, immediately above the Price formation andesite.

Price formation andesite is over 300 m thick in the vicinity of the camp and consists of feldspar ± pyroxene phryric basaltic andesite flows. Synvolcanic block faulting of this unit formed the regional-scale Buttle Lake camp basin with a strike length of at least 10 km. Local sub-basins in this major structure contain the sulfides and felsic volcanic rocks of the H-W horizon.

The H-W horizon is a 15- to 200-m-thick felsic package that extends throughout the basin. It consists of eight members, three of which represent periods of massive sulfide deposition. From the stratigraphic base to the top of these members are (1) the Battle Main massive sulfide lens, (2) fine rhyolitic tuffaceous deposits, (3) H-W massive sills, (4) Gap massive sulfide lens, (5) coarse rhyolite pyroclastic deposits, (6) rhyolite tuffaceous and cherty sediments, (7) Battle Upper massive sulfide lenses, and (8) a tripartite rhyolite flow-dome complex consisting of quartz porphyry phryic rhyolite, quartz-feldspar porphyry rhyolite, and green quartz-feldspar porphyry rhyolite. Volcaniclastic units in the felsic package evolved with interfingering of subaerial and submarine pyroclastic processes. Flow-dome units evolved by fractionation of quartz and feldspar.

Alteration, evaluated petrographically and with Pearce element ratios, is most intense close to synvolcanic and synmineral feeder faults that channeled solutions through the Price formation andesite proximal to the Battle Main massive sulfide lens. Envelopes to the feeder faults have distinctive Mg addition anomalies and contain the mineral assemblage pyrite > sericite > quartz > chlorite. Discharge feeder stockworks immediately below the Battle Main massive sulfide lens contain varying proportions of sericite, quartz, and pyrite but lack significant chlorite. Deposition of the H-W horizon pyroclastic units on top of the Battle Main massive sulfide lens did not halt mineralization. Rather, fluids continued to percolate upward through the newly deposited pyroclastic units and deposited the Battle Upper lenses close to the new sediment-water interface. Alteration below the Battle Upper lenses consists of quartz, sericite, and pyrite with minor galena, sphalerite, and tennantite. Overall, hydrolysis of feldspar in both the Price formation and the H-W horizon resulted in a halo surrounding the ore lenses marked by addition of K and concomitant Na and Ca depletion.

Introduction

The Buttle Lake mining camp (49°34' N, 125°36' W), near central Vancouver Island in Strathcona Park at the south end of Buttle Lake, is 90 km southwest of the Campbell River, British Columbia (Fig. 1). It is a major volcanogenic massive sulfide district in which deposits are hosted by the Myra formation of the Paleozoic Sicker Group. Past production has come from several mines (Fig. 2): Lynx (open pit and underground), Myra (open pit), and H-W (underground). Continuous operation over the last 25 years has produced more than 13 Mt of ore. The Price deposit, discovered early in the history of the camp (ca. 1917), has received sporadic development work but has not been mined. Current geologic reserves (Pearson, 1993; Westmin Resources Ltd., Annual Report, 1994) are about 12.5 Mt of proven and probable massive sulfide ore grading 2.0 g/t Au, 46.1 g/t Ag, 1.9 percent Cu, 0.5 percent Pb, and 7.1 percent Zn. The H-W mine has the largest reserve with almost 8 Mt.

The Battle zone (Fig. 2) was discovered in 1991 as part of an ongoing, camp-scale exploration program. It is a significant zone with about 2.3 Mt of proven and probable massive sulfide ore grading 1.3 g/t Au, 25.3 g/t Ag, 2.5 percent Cu, 0.5 percent Pb, and 13.2 percent Zn.

Massive sulfide lenses within the Buttle Lake mining camp are spatially and temporally related to two cycles of felsic volcanism in the Myra formation. The first cycle is represented by the H-W horizon; the second by the Lynx-Myra-Price horizon. Lenses associated with the H-W horizon include (Fig. 2) the H-W Main, H-W North, H-W Main Extension, Battle Main, Gap, and Ridge West. Most of these ore lenses occur at the base of the H-W horizon, at or close to the Price formation contact (Figs. 3 and 4). The Price formation is the lowest unit of the Sicker Group in the Buttle Lake uplift (Juras, 1987). The Lynx-Myra-Price felsic cycle is associated with the smaller Lynx, Myra, and Price lenses (Fig. 2).

The H-W horizon is associated with deposition of the
largest orebodies in the camp (e.g., the H-W Main and Battle Main lenses). Consequently, current research (Barrett et al., 1994; Robinson, 1994; Robinson et al., 1994; Godwin et al., 1996; Robinson and Godwin, in prep.) is focused on defining the stratigraphy within and around the H-W horizon and establishing relationships between felsic volcanism and massive sulfide deposition in the H-W horizon. This paper presents geologic, lithogeochemieal, and alteration aspects of the Battle zone following a detailed study by Robinson (1994).

Regional and Mine Geology

Regional geology

Massive sulfide deposits of the Buttie Lake mining camp occur within the Myra formation of the Paleozoic Sicker Group. The Sicker Group is the oldest stratigraphic unit recognized on Vancouver Island, and represents the exposed base of Wrangellia, an allochthonous terrane that underlies most of the island (Jones et al., 1977). The Sicker Group is exposed in three major fault-bounded uplifts: Buttie Lake, Cowichan-Horne Lake, and Nanoose (Fig. 1). The Buttie Lake camp occurs in the Buttie Lake uplift. An informal revised stratigraphy for the Buttie Lake uplift, established by Juras (1987; cf. Robinson et al., 1994), incorporates earlier work by Fyles (1955), Yole (1969), Jeffery (1970), Sada and Danner (1974), Muller (1980), and Brandon et al. (1986). The Sicker Group, in order of decreasing age, varies from Late Devonian (or older) to Early Permian or Early Triassic. Informally recognized formations by decreasing age are Price, Myra, Thelwood, Flower Ridge, Buttie Lake Limestone, and Henshaw.
Mine geology: Myra formation

The Myra formation is a complex sequence of mafic to rhyolitic volcaniclastic rocks and lesser flow units that fills the northwest-trending Buttle Lake camp basin. All important ore lenses are in the Myra formation. The largest are immediately above the contact with the underlying Price formation. The Myra formation is characterized by relatively continuous units that trend northwesterly but have rapid northeasterly to southwesterly facies variations (Walker, 1985). Juras (1987) recognized ten lithostratigraphic units in the Myra formation. They are, from the bottom up, the H-W horizon, the hanging-wall andesite, the ore clast breccia, lower mixed volcaniclastic rocks, the upper dacite-5E andesite, the Lynx-Myra-Price horizon, the G flow, upper mixed volcaniclastics, the upper rhyolite, and the upper mafic units ("horizon" is used informally). Descriptions of these lithologic units are in Juras (1987), Juras and Pearson (1990), and Pearson (1993).

Geology of the Battle Zone

Massive sulfide lenses in the Battle zone occur at three stratigraphic levels within the H-W horizon: at the underlying Price formation contact (Battle Main zone), overlying both andesitic rocks and felsic tuffs (Gap lens), and at the contact between rhyolite volcaniclastics and an overlying rhyolite flow-dome complex (Battle Upper lenses). The Gap lens is about 100 m above the Battle Main zone; this most likely reflects the paleotopography of the Price andesite during massive sulfide deposition, but could be a result of postmineral displacement. Geology of the Battle and Gap zones is complicated by synmineral and postmineral faulting, rapid facies changes, and texturally destructive alteration. To understand the depositional environment better, a detailed stratigraphy of the H-W horizon was established in the Battle zone (Fig. 3). Representative cross sections are found in Figure 4a and b (section 13 + 72E and section 15 + 85E, respectively).

Lithology: Price formation

The Price formation is a sequence of massive to pillowed basaltic andesite flows, volcanic breccias, interflow clastic sediments, and turbidites. It is over 300 m thick and is the lowermost unit in the mine area and the Buttle Lake uplift (Juras, 1987). The base has not been identified. Only the upper 75 m of the formation has been intersected in Battle zone exploration drilling. All of these drill hole intersections are intensely altered; primary volcanic and depositional textures are preserved only sporadically.

Two types of andesite flows in the Price formation were defined by Juras (1987) based on phenocryst assemblages. They are either clinopyroxene-feldspar porphyritic or feldspar porphyritic. Contacts to individual flow units may be sharp with devitrified chill margins or gradational into hyaloclastite.
In situ and resedimented hyaloclastite breccia

Andesite flow

Green quartz–feldspar–porphyritic rhyolite

Quartz–feldspar–porphyritic rhyolite

Feldspar–quartz–hornblende rhyolite porphyry dike

Laminar flow-banding
Bottom-flow breccia
Tennantite-rich massive sulphide

Rhyolite tuffaceous sediments with local beds of accretionary(?)-lapped

Rhyolite tuff with pumice blocks
Pumiceous lapilli tuff
Laminated, cherty rhyolite fine tuff (FRTD)
Peperite

In situ hyaloclastite breccia

Thin-bedded massive sulphide
Yellow sphalerite–rich
Banded block sphalerite and chalcopyrite+pyrite
Chalcopyrite–rich

Massive to pillowed flows and flow breccia

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deposits up to 6 m thick (Fig. 5). Pillow breccia is common. Pillow fragments are scoriaceous and have convex edges.

Minor interflow sediments consist of gray to green-gray wacke. They are moderately well sorted to well sorted and fine upward; some are turbidites.

Lithology: H-W horizon

The H-W horizon consists of the following eight members in the Battle zone from bottom up (Fig. 3): the Battle Main massive sulfide lens, fine rhyolitic tuffaceous and chert deposits, H-W mafic sills, the Gap massive sulfide lens (tentatively assigned here), coarse rhyolite pyroclastic deposits, rhyolite tuffaceous sediments, Battle Upper massive sulfide lenses, and a rhyolite flow-dome complex. These members, detailed on cross sections in Figure 4a and b, are described below.

The Battle Main massive sulfide lens (Figs. 3, 4, and 6): The lens occurs at the contact between the basaltic andesite of the Price formation and the dominantly felsic volcanic units of the H-W horizon. The Battle Main massive sulfide lens ranges from 130 to 210 m wide and 4 to 25 m thick. It has a minimum strike length of 500 m and is open at both ends, but it is bounded to the north by a subvertical normal fault. It is mineralogically zoned (Robinson and Godwin, in prep.) from footwall sericite-quartz-pyrite stockwork mineralization that is in the Price formation andesite, through chalcopyrite-rich massive sulfide (Fig. 6a), banded massive sulfide mineralization in the central region (Fig. 6b), pale yellow massive sphalerite at the top and periphery (Fig. 6c), and laminated or bedded massive sulfides locally preserved at the top of the yellow sphalerite zone (Fig. 6d).

Fine rhyolitic tuffaceous and chert deposits (Figs. 3, 4, and 7): These deposits occur above the Battle Main massive sulfide lens but below the Gap lens. Deposits consist of thinly bedded fine tuff (Fig. 7a) and tuffaceous chert (Fig. 7b). Massive gray, purple, or green tuffaceous chert (Fig. 7b) forms a distinctive, but discontinuous, marker up to 5 m thick (Fig. 4b) above the Battle Main massive sulfide zone. The tuffaceous component commonly comprises about 1 percent broken quartz crystals and 8 percent fine-grained sericite. Feldspar grains are absent or altered beyond recognition. Sulfides occur locally as thin beds or laminae of pyrite and sphalerite, and as stringers of quartz, chalcopyrite, sphalerite, and pyrite.

H-W mafic sills (Figs. 3, 4, and 8): The sills are 5 to 30 m thick and intrude both the upper 30 m of the Price formation and the felsic volcaniclastic rocks of H-W horizon (Figs. 3 and 4). The physical appearance of the sills is largely dependent upon the unit intruded.

Sills within the felsic volcaniclastic rocks in the westernmost part of the Battle zone (Fig. 4a) are massive. They are generally pink due to pervasive sericite-pyrite alteration (Fig. 5a) and have upper contacts marked by globular peperite (cf. Busby-Spera and White, 1987). Swirls of white tuffaceous material are incorporated into sill margins that have been altered to yellow-brown palagonite (Fig. 5b).

Sills that intrude the Price formation andesite have sharp contacts. They also tend to be dark brown to green-brown. In some areas, H-W mafic sills are texturally indistinguishable from Price formation andesite.
Gap massive sulfide lens (Figs. 4a and 9): This lens is a polymetallic orebody about 20 to 30 m high, 40 to 50 m wide, and about 250 m long (Pearson, 1993). It is located (Fig. 4a) about 200 m northeast and about 50 m above the Battle Main massive sulfide zone. The Gap massive sulfide lens is zoned (Robinson and Godwin, in prep.) from footwall sericite-quartz-pyrite stockwork mineralization that is in andesitic rocks, thinly laminated felsic tuff, and quartz porphyritic rhyolite, through lower pyritic massive sulfide and upper and peripheral baritic massive sulfide. Pyritic massive sulfides (Fig. 9a) contain pyrite, sphalerite, chalcopyrite, bornite, and tennantite, with minor anilite, colusite, and renierite. Baritic massive sulfide from the upper part of the Gap lens (Fig. 9b) contains sphalerite, barite (locally mammillary with convex surfaces up), pyrite, quartz, galena, chalcocpyrite, and tennantite.

Coarse rhyolite pyroclastic deposits (Figs. 3, 4, and 10): These are composed of two related members that form a distinctive marker horizon. These are pumiceous lapilll tuff, and rhyolite tuff with pumice blocks.

Pumiceous lapilli tuff (Fig. 10a and b) is about 3 m thick, but locally reaches thicknesses greater than 10 m. It contains about 15 percent cognate lithic fragments of quartz porphyritic rhyolite, 10 percent whole and broken quartz crystals, and 5 percent accidental lithic clasts of sulfide, chert, mafic volcanic rock, and pale green mudstone supported in a matrix of compacted, sericitized pumice fragments. The pumiceous component is dark gray-green to black and is altered to sericite. It has a eutaxitic texture that appears to reflect welding (figs. B2–B4 in Juras, 1987). Baked mudstone fragments and pyrrhotite-altered sulfide fragments observed by Juras (1987) in less altered equivalents of this unit further support high-temperature deposition. Quartz porphyritic rhyolite fragments are angular to subangular. The unit is normally graded and fines from fragments over 5 cm in diameter at the base of the unit to 0.5 cm at the top. Characteristic quartz phenocrysts distinguish these lithic fragments from occasional accidental chert fragments or mudstone fragments.

Rhyolite tuff with pumice blocks forms deposits between 20 cm and 2 m thick on top of the pumiceous lapilli tuff, particularly in the western part of the Battle zone (Fig. 4a). This unit is characterized by conspicuously large fragments
up to 30 cm across of black, sericitized, flattened, crystal-rich pumice. These blocks are supported in a well-sorted, laminated matrix of coarse to fine tuff. Thin beds of white, cherty material about 10 cm thick separate individual sub-units. These beds are probably silicified ash-siltstone suspension-sediment layers (R. Allen, Volcanic Resources Ltd., written commun., 1993).

Rhyolitic tuffaceous sediments (Figs. 3, 4, and 11): The sediments consist of 5- to 50-m-thick deposits of ash, fine tuff, coarse tuff, and other volcanic products. Most of these deposits are featureless due to pervasive sericite alteration and abundant veins of sphalerite, tennantite, galena, and pyrite (Fig. 11a). Occasional devitrified spherulitic obsidian fragments occur throughout the unit. Silicified tube-pumice was identified in the southeastern part of the Battle zone. In the northwestern part at the top of the unit, a 3-m-thick bed of accretionary lapilli was observed. The ellipsoidal lapilli (Fig. 11b), from 2 to 10 mm across, locally contain nuclei of

FIG. 5. Price formation andesite. Coin is 8 mm in diameter. In situ andesite hyaloclastite (Fig. 4a: DDH 14–754, 340 m). Large olive-green fragments contain 10 percent quartz-chlorite-filled amygdules about 0.5 to 10 mm across. Pale green grains are saussuritized feldspar. Dark green-black fragments are devitrified volcanic glass that have been partially replaced by pyrite.

Fig. 6. Battle Main massive sulfide. Coin is 8 mm in diameter. (a). Chalcopyrite-rich ore from the basal part of the sulfide lens (Fig. 4a: DDH 14–751, 323.4 m). (b). Banded pyrite and dark sphalerite from the middle part of the sulfide lens (Fig. 4a: DDH 14–751, 321.3 m). (c). Pale yellow sphalerite from the top of the sulfide lens (Fig. 4a: DDH 14–751, 318.8 m). Sample, almost pure sphalerite, contains only 5 percent pyrite and 10 percent gangue. (d). Interbedded sphalerite, pyrite, and shale from the top of the sulfide lens (Fig. 4a: DDH 14–753, 280 m). Bedding to core axis angles in the sulfide unit are the same as in the overlying fine rhyolitic tuffaceous deposits. Chalcopyrite and galena are concentrated in de-watering pillar structures that are perpendicular to bedding.

Fig. 7. Fine rhyolitic tuffaceous and chert deposits (Fig. 3, FRTD). Coin is 8 mm in diameter. (a). Fine rhyolitic tuff (Fig. 4a: DDH 14–751, 291 m). Dark gray layer on the left is mostly flattened pumice fragments with 10 percent 1-mm quartz crystals. Pale gray layer is fine silicified rhyolitic tuff with quartz veins perpendicular to bedding. Layer at right (top) is coarse rhyolitic tuff. It contains 0.5 percent quartz crystals and 2 percent black devitrified pumice fragments. (b).
White, distinctively laminated tuffaceous chert (Fig. 4a: DDH 14–751, 306 m). Quartz and sulfide veins crosscut laminations at 90°.

Fig. 8. H-W mafic sill (Fig. 3). Coin is 8 mm in diameter. (a). Massive sill (Fig. 4a: DDH 14–753, 268 m). The sample is pink due to pervasive sericite-pyrite alteration. (b). Swirly yellow-brown and white pumice from the top of the sill (Fig. 4a: DDH 14–753, 263 m). White material, incorporating felsic tuffaceous sediment from overlying units, is siliceous and contains euhedral quartz crystals. The yellow-brown material is palagonite.

Fig. 9. Gap massive sulfide lens. Coin is 8 mm in diameter. (a). Pyritic massive sulfide (Fig. 4a: DDH 14–757, 223.7 m). Mineralogy is pyrite sphalerite bornite anilite. (b) Baritic massive sulfide from the upper part of the Gap lens (Fig. 4a: DDH 14–757, 200 m). Mineralogy is sphalerite barite pyrite quartz galena tennantite. Barite to right of center shows mammillary convex surfaces that face up-hole (to the right).

Fig. 10. Coarse rhyolite pyroclastic deposits (Fig. 3). (a). Pumiceous lapilli tuff (Fig. 4a: DDH 14–753, 254 m; coin is 8 mm in diameter) contains 15 percent pale gray to white weakly quartz-porphyritic to aphanitic rhyolite fragments in a black, compacted, pumiceous, crystal-rich matrix with 10 percent 2-mm quartz eyes and 15 percent 2-mm feldspar crystals.
Fig. 10. (Cont.) (b). Photomicrograph (crossed polars) of pumiceous lapilli tuff (Fig. 4b: DDH 14–906, 284 m). Sample contains a fine-grained lithic fragment in the center. Surrounding material is sericite with 10 percent broken quartz crystals.

Fig. 11. Rhyolite tuffaceous sediments. Coin is 8 mm in diameter. (a). Tuffaceous sandstone (Fig. 4a: DDH 14–750, 260 m). Specimen is intensely sericitized and altered by polymetallic quartz-sericite veins, but relict sedimentary bedding is visible. (b). Photomicrograph (plane light) of a 3-mm-long accretionary lapillus (Fig. 4a: DDH 14–754, 251 m). Although the sample is pervasively sericitized, the concentric organization of pyroclasts is clear. Note the central nucleus of broken quartz.

Fig. 12. Battle Upper massive sulfide. Coin is 8 mm in diameter. Specimen contains sphalerite tennantite pyrite galena chalcopyrite and grades over 1,000 g Ag/t.

Fig. 13. Rhyolite flow-dome complex. Coin is 8 mm in diameter. (a). Quartz-porphryitic rhyolite (QP) with 2 percent 1-mm quartz eyes and trace spherulites (Fig. 4a: DDH 14–957, 266 m). (b). Photomicrograph of the quartz porphyritic rhyolite (Fig. 4a: DDH 14–757, 276 m; crossed polars). This photo shows characteristic euhedral to subhedral, locally square quartz phenocrysts about 0.8 mm across in an aphanitic groundmass. Inset is a photomicrograph (crossed polars)
broken quartz crystals. Dark concentric zones in the lapilli are clearly visible in plane light (Fig. 11b; cf. Boulter, 1987) and are fine ash. The lapilli are pervasively sericitized.

**Battle Upper massive sulfide lenses (Figs. 3, 4, and 12):** These lenses occur mostly at the contact between rhyolite tuffaceous sediments and the overlying quartz-feldspar porphyritic rhyolite, but may also be enclosed by the rhyolitic tuffaceous sediments. Individual lenses range from 1 to 8 m thick, but are typically less than 20 m wide. They are discontinuous along strike, so it is not possible to follow most of them between exploration drilling sections, which are spaced 50 to 100 m apart. The larger lenses (Robinson and Godwin, in prep.) have a core region containing sphalerite, tennantite, pyrite, galena, and chalcopyrite; massive barite and sphalerite occur on the periphery. Massive sulfide lenses are underlain by feeder zones composed of polymetallic veins in altered rhyolitic tuffaceous sediments. These veins contain pyrite, sphalerite, tennantite, and quartz; grades of more than 1,000 g Ag/t are common. The veins are surrounded by pervasively sericitized and silicified felsic rocks.

**Rhyolite flow-dome complex (Figs. 3, 4, and 13; Table 1):** The complex extends northward and southeast of the Battle zone for a total strike length of at least 3 km; it is unexplored at both ends. In the Battle zone, the flow-dome complex is between 5 and 120 m thick, thickens to the northeast, and is at least 200 m wide. The northeastern part of the complex has not been defined by the current drilling, because it has apparently been faulted downward (C. Pearson, Westmin Resources Ltd., pers. commun., 1993).

### Table 1. Mineralogy of Individual Members within the Rhyolite Flow-Dome Complex, Battle Zone, Buttle Lake Mining Camp

<table>
<thead>
<tr>
<th>Figure no.</th>
<th>Quartz-porphyritic rhyolite</th>
<th>Quartz-feldspar porphyritic rhyolite</th>
<th>Green quartz-feldspar porphyritic rhyolite</th>
</tr>
</thead>
<tbody>
<tr>
<td>13a, b</td>
<td></td>
<td>13c, d, e</td>
<td>13f</td>
</tr>
<tr>
<td>Quartz phenocrysts</td>
<td>2%, 0.5–2 mm</td>
<td>4%, 0.5–5 mm</td>
<td>6%, 0.5–6 mm</td>
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<tr>
<td>Morphology of quartz phenocrysts</td>
<td>Subhedral to euhedral, after tetragonal cristobalite crystals</td>
<td>Euhedral to slightly embayed dominantly hexagonal crystals, 1% after cristobalite crystals</td>
<td>Strongly embayed with rims of quartz and feldspar</td>
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<tr>
<td>Feldspar phenocrysts</td>
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<td>8%, 3 mm</td>
<td>10%, 1–10 mm</td>
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<tr>
<td>Hornblende phenocrysts</td>
<td>None</td>
<td>None</td>
<td>Rare</td>
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<tr>
<td>Accessory minerals</td>
<td>Rare</td>
<td>Apatite, zircon</td>
<td>Magnetite</td>
</tr>
<tr>
<td>Matrix</td>
<td>Very fine grained quartz and sericite, perhaps after felspar microlites</td>
<td>Fine-grained quartz and feldspar</td>
<td>Fine-grained quartz, feldspar and chlorite</td>
</tr>
</tbody>
</table>

1 All rhyolite units contain oligoclase of composition An40, determined by the Michel-Levy method: staining shows that there are no K feldspar phenocrysts; all feldspars are altered to sericite and carbonate, but the degree of alteration decreases with decreasing age (from left to right).

Three distinctive units in the rhyolite flow-dome complex were distinguished and mapped based on the presence, size, and morphology of quartz and feldspar phenocrysts (Table 1; cf. de Rosen-Spence et al., 1980). All rhyolite types contain quartz and oligoclase (An40). The three members, from stratigraphic base to top, are quartz porphyritic rhyolite (QP; Fig. 13a and b), quartz-feldspar porphyritic rhyolite (QFP; Fig. 13c–e), and green quartz-feldspar porphyritic rhyolite (GQFP; Fig. 13f).

Quartz porphyritic rhyolite (QP; Fig. 13a and b) is 5 to 30 m thick, at least 75 m wide, and at least 250 m long. It occurs both within the felsic volcaniclastic sequence in the northeastern part of the Battle zone (Fig. 4b) and in andesite below the Gap massive sulfide lens (Fig. 4a). Contact relationships between the quartz porphyritic rhyolite and other lithologic units are not clear enough in drill core to define a mode of emplacement. However, its occurrence in lithologic units of different ages suggests that it is a shallow-level sill rather than a flow.

The quartz porphyritic rhyolite is white to pale gray-green (Fig. 13a) and contains 1 to 2 percent subhedral to euhedral hexagonal and characteristic square quartz phenocrysts (after cristobalite) about 1 mm in diameter (Fig. 13b). Most quartz crystals have sharp boundaries; rare crystals are embayed and some have quartz-feldspar coronas. Trace sericite-altered feldspar phenocrysts are also present. The matrix has a granophyritic texture and is composed of fine-grained, roughly equidimensional, recrystallized quartz and feldspar. Locally, the matrix is weakly flow-banded; pyrite and sericite are con-

of a spherulite 0.13 mm across showing sector extinction. (c). Dark gray quartz-feldspar porphyritic rhyolite (QFP) from the base of the flow-dome complex (Fig. 4a: DDH 14–753, 221.9 m). Sample contains 4 percent 2-mm quartz eyes and 15 percent 2-mm sericitized feldspar. Flow-bands are marked by trails of pyrite grains. (d). Photomicrograph of quartz-feldspar porphyritic rhyolite (Fig. 4b: DDH 14–905, 232 m; crossed polars). Sample contains subhedral quartz grains 1 mm across, and albite grains 0.4 to 1.5 mm long. (e). Autobrecciated, flow-folded quartz-feldspar porphyritic rhyolite from the margin of the rhyolite flow-dome complex (Fig. 4a: DDH 14–756, 242 m). (f). Green quartz-feldspar porphyritic rhyolite (Fig. 4b: DDH 14–904, 284 m) is characterized by abundant albite phenocrysts in a green matrix. (f). Green quartz-feldspar porphyritic rhyolite from the hanging-wall andesite. Scale is in centimeters. Corroded fragments of andesite that can be jigsawed together are characteristic of this unit.

*Fig. 14.* Hyaloclastite breccia from hanging-wall andesite. Scale is in centimeters. Corroded fragments of andesite that can be jigsawed together are characteristic of this unit.

*Fig. 15.* Feldspar-quartz-hornblende-rhyolite porphyry dike (QFPD): (a) Massive, green-gray feldspar-quartz-hornblende porphyry dike (Fig. 4a: DDH 14–753, 221.8 m) with 35 percent 3-mm feldspar crystals and 10 percent 3-mm quartz eyes. Green color is due to chlorite alteration of mafic minerals in the matrix. This unit crosscuts the rhyolite units described above.
centrated along the flow bands. This unit is intensely sericitized due to its proximity to ore-forming hydrothermal systems. Hydrothermally altered flows, easily mistaken for tuffaceous chert units, are distinguishable from chert by the presence of quartz phenoerysts.

Quartz-feldspar porphyritic rhyolite (Fig. 13c-e) is the most abundant rhyolite type within the Battle zone. It is between 30 to 60 m thick in the central and northeastern regions of the Battle zone. To the southwest, between 4200N and 4100N (Fig. 4), the unit thins into lobes between 5 and 10 m thick. The upper contact with overlying andesite flows and volcaniclastic rocks is rubbly. The lower contact sharply overlies quartz-feldspar porphyritic rhyolite and the felsic tuffs overlying the Gap volcaniclastic rocks. The above morphological variations within the quartz-feldspar porphyritic are consistent with it being a volcanic flow rather than a sill.

The quartz-feldspar porphyritic is characterized petrographically by about 8 percent sericite-carbonate-altered feldspar phenocrysts and by about 4 percent euhedral to slightly embayed quartz phenocrysts in an aphanitic and weakly flow-banded matrix (Fig. 13c-e). Locally, feldspar crystals grow around quartz crystals, indicating that quartz crystallized first. Both hexagonal and square (after cristobalite) cross sections of quartz are apparent in thin sections. Some crystals have thin rims of intergrown quartz and feldspar. Accessory apatite and zircon occur.

Green quartz-feldspar porphyritic rhyolite (Fig. 13f) forms flows 5 to 50 m thick that occur on top of the quartz-feldspar porphyritic rhyolite and the felsic tuffs overlying the Gap massive sulfide lens (Fig. 4a). Most of the green quartz-feldspar porphyritic rhyolite occurs in the northern part of the Battle zone, although a detached lobe between 5 and 20 m thick was mapped toward the south in Figure 4b (about 4100N). The upper contact with the hanging-wall andesite is rubbly and somewhat reworked; this contact most likely represents a brecciated flow carapace. Locally, the upper part of the green quartz-feldspar porphyritic rhyolite is hematitic, suggesting a period of exposure on the sea floor.

The green quartz-feldspar porphyritic rhyolite contains about 6 percent subhedral to rounded quartz phenocrysts and 10 percent feldspar phenocrysts (Fig. 13f). Many of the quartz crystals are deeply embayed and are rimmed with intergrown quartz and feldspar. Square quartz crystals are notably absent. Feldspars are altered to sericite and carbonate, but less so than in the quartz porphyritic rhyolite and the quartz-feldspar porphyritic rhyolite. The matrix is mostly fine-grained granophyric quartz and feldspar. Chlorite, possibly replacing hornblende, occurs in the matrix with disseminated opaque magnetite.

**Hanging-wall andesite**

Hanging-wall andesite in the Battle zone occurs as shallow-level sills intruding well-sorted, andesite-dominant graywacke or poorly sorted polymict breccia. Most sills have a 2- to 5-m-thick coherent core that grades into jigsaw-fit hyaloclastite (Fig. 14). The jigsaw-fit texture is characteristic of intrusion into wet sediment (McPhie et al., 1993). The contact between the underlying H-W horizon and the hanging-wall andesite is generally sharp, although fragments of quartz-feldspar porphyritic and green quartz-feldspar porphyritic rhyolite are commonly scoured from the flow-dome complex and incorporated into the overlying andesite. Hydrothermal alteration that affects the Price formation and the H-W horizon does not extend into the hanging-wall andesite, suggesting a hiatus between hydrothermal alteration and deposition of the hanging-wall andesite.

Hanging-wall andesite is dark green, slightly amygdaloidal, and contains about 25 percent feldspar and 1 percent pyroxene phenocrysts. The felsic tuffs occurs as glomerocrysts or freely in the matrix. Most feldspar is moderately to intensely altered to calcite and epidote. Chlorite replaces rare pyroxene phenocrysts. The amygdalae are elongate to lenticular and are filled with quartz, epidote and magnesian chlorite. The matrix is pervasively altered to magnesian chlorite and clinozoisite, and contains traces of magnetite.

**Dikes**

Most dikes in the Battle zone are mafic. Three distinct types of mafic dikes have been recognized: pale green, feldspar porphyritic, trachytic mafic dikes, dark green augite and feldspar porphyritic mafic dikes, and andesite dikes. Most of the pale green dikes are intensely altered to an epidote-fuchsite-chlorite-carbonate assemblage and have irregular, quartz-carbonate veined contacts with the country rock. Some dikes have pink quartz-carbonate-filled amygdalae. Dark green augite porphyritic dikes may be fresh or altered to epidote, fuchsite, and chlorite; they have sharp contacts. Andesite

![Graph](Image)

**Fig. 16.** Plot of TiO₂ versus Zr for the H-W horizon rhyolite (open squares) and Price formation andesite (filled triangles) sampled from the Battle zone, Battle Lake mining camp. Least altered rocks, classified on the basis of petrography, are presented in Table 2 and annotated with “F” above the data point in this plot. Samples of the H-W horizon rhyolite form a linear array, given measurement error, that passes through the origin, suggesting that these samples were derived from a common parent melt and that TiO₂ and Zr are conserved elements (Stanley and Madeisy, 1994). In contrast, Price formation andesites form a fan-shaped array through the origin. This may be because TiO₂ is not completely conserved, TiO₂ commonly occurs in minor amounts in clinopyroxene, a phenocryst observed in these rocks that may have undergone crystal sorting, with consequent mobilization of TiO₂.
<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Drill hole</th>
<th>Depth (m)</th>
<th>Price formation andesite</th>
<th>Price formation andesite</th>
<th>Price formation andesite</th>
<th>Price formation andesite</th>
<th>Price formation andesite</th>
<th>Price formation andesite</th>
<th>Chert&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Pumicous lapilli tuff&lt;sup&gt;4&lt;/sup&gt;</th>
<th>Rhyolitic tuffaceous sediments&lt;sup&gt;5&lt;/sup&gt;</th>
<th>Quartz-porphyritic rhyolite&lt;sup&gt;6&lt;/sup&gt;</th>
<th>Quartz-porphyritic rhyolite&lt;sup&gt;6&lt;/sup&gt;</th>
<th>Quartz-porphyritic rhyolite&lt;sup&gt;6&lt;/sup&gt;</th>
<th>Quartz-porphyritic rhyolite&lt;sup&gt;6&lt;/sup&gt;</th>
<th>Green quartz-porphyritic rhyolite&lt;sup&gt;6&lt;/sup&gt;</th>
<th>Green quartz-porphyritic rhyolite&lt;sup&gt;6&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>229WR</td>
<td>W122D</td>
<td>844.4</td>
<td>267.1</td>
<td>254.3</td>
<td>283.2</td>
<td>282.6</td>
<td>285.1</td>
<td>14-909</td>
<td>14-907</td>
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<td>14-990</td>
<td>14-991</td>
<td>14-991</td>
<td>14-991</td>
<td>14-904</td>
<td>14-753</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Geochemical Analyses of Least-Altered Rocks from the Battle Zone<sup>1</sup>, Buttle Lake Mining Camp**

**Wt percent**

<table>
<thead>
<tr>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>P₂O₅</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>MgO</th>
<th>CaO</th>
</tr>
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<tbody>
<tr>
<td>52.9</td>
<td>0.83</td>
<td>16.4</td>
<td>9.55</td>
<td>4.21</td>
<td>5.55</td>
<td>4.12</td>
<td>0.49</td>
<td>0.26</td>
<td>0.14</td>
<td>0.14</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Parts per million**

<table>
<thead>
<tr>
<th>Ni</th>
<th>Co</th>
<th>Cu</th>
<th>Pb</th>
<th>Zn</th>
<th>Ga</th>
<th>S</th>
<th>As</th>
<th>Se</th>
<th>Nb</th>
<th>Sr</th>
<th>Rb</th>
<th>Zr</th>
<th>Y</th>
<th>Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>19.3</td>
<td>73</td>
<td>5.4</td>
<td>89</td>
<td>17.2</td>
<td>25,900</td>
<td>3</td>
<td>25.8</td>
<td>0.5</td>
<td>434</td>
<td>7.2</td>
<td>81.7</td>
<td>32.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>

3.57

**L.O.I. = limit of ignition**

<sup>1</sup> Rock units are spatially located in Figures 3 and 4.

<sup>2</sup> Samples are from outside the Battle zone.

<sup>3</sup> Analyses are from Juras (1987), analytical details and associated errors are also in Juras (1987).

<sup>4</sup> Detailed location is available from Robinson (1994).

<sup>5</sup> Analyzed by X-Ray Laboratories Ltd., Don Mills, Ontario; analytical details and associated errors are in Robinson (1994).

<sup>6</sup> Analyzed in 1993 at Geochemical Laboratories, Earth and Planetary Sciences, McGill University, Montreal, Quebec; analytical details and associated errors are in Robinson (1994).
dikes are dark blue-green, weakly feldspar porphyritic, and unaltered. All of these mafic dikes cross-cut the H-W horizon and the hanging-wall andesite.

One feldspar-quartz-hornblende porphyry dike (Fig. 15) was identified in the Battle zone. It has sharp, quenched contacts with the quartz-feldspar porphyritic rhyolite and clearly crosscuts it as shown in Figure 4a (about 4200N). The feldspar-quartz-hornblende porphyry dike is clearly younger than all other units in the H-W horizon. It may represent a feeder dike to felsic units in the upper Myra formation, Jurassic intrusive activity, or Tertiary intrusions (S. Juras, Westmin Resources Ltd., written commun., 1994).

Lithogeochemistry

Variations in the chemical compositions of volcanic rocks that host hydrothermal mineral deposits are generally caused by measurement error; closure, a mathematical constraint that requires the sum of all element concentrations in a rock to equal unity; rock-forming processes (e.g., crystal sorting); and hydrothermal metasomatism (Stanley and Madeisky, 1994).

Measurement errors cannot be avoided and thus are propagated through numerical calculations and compared with observed compositional variations. Lithogeochemical variations due to closure may be removed mathematically using Pearce element ratios (PER; Russell and Nicholls, 1988) if the rocks under consideration meet the following conditions: the rocks are related to a common parent (i.e., co-genetic) that was at one time homogeneous, at least one element was not involved in material transfer (i.e., conserved), and at least one material transfer process (e.g., fractionation, metasomatism) has acted to create geochemical variability.

Pearce element ratios are based on molar compositions. They are calculated using the following formula (Russell and Nicholls, 1988): \[ \text{PER}_{ij} = \frac{(W_jA_j/M_j)}{(W_iA_i/M_i)}, \] where \( W_{ij}, A_{ij}, \) and \( M_{ij} \) are weight percentages, the number of cations in the oxide formula, and the molecular weight of the elements i and j, respectively. Element j is conserved.

Conserved elements in the H-W horizon rhyolite and the Price formation andesite are identified in Figure 16. Samples of H-W horizon rhyolite form a linear array, given measurement error, that passes through the origin, suggesting that these samples were derived from a common parent melt and that TiO\(_2\) and Zr are conserved elements (Stanley and Madeisky, 1994). Petrographic observations support the above conclusion. Within the H-W horizon rhyolite, TiO\(_2\) is not contained in feldspar or quartz, the major phenocryst minerals that have undergone material transfer. Zr, although it resides in sparse and small zircon crystals, probably did not fractionate because the small grain size would not allow preferential sorting in a viscous rhyolite melt. In contrast, data from the Price formation andesite form a fan-shaped array through the origin. This dispersion of data may reflect crystal sorting of TiO\(_2\)-bearing clinoxyroxene, a phenocryst commonly observed in this unit. Zr, however, does not occur in any phenocrysts that underwent material transfer in the Price formation. Consequently, Zr is the best common choice for a conserved element in both lithologies, and has been used to construct Pearce element ratios in the following analysis.

Lithogeochemical variation due to igneous fractionation (rock-forming process), and hydrothermal metasomatism (ore-forming process) can be decoupled and modeled graphically using Pearce element ratios diagrams (Russell and Stanley, 1990). These diagrams allow testing of petrologic hypotheses that model the specific fractionation effects in both the H-W horizon rhyolite and the Price formation andesite. Once these hypotheses are validated using fresh samples (Table 2), geochemical data that depart from these fractionation models can be interpreted as having been affected by hydrothermal metasomatism. Specifically, the degree of departure from the fractionation line is a measure of the amount of metasomatism the rocks have undergone (Stanley and Madeisky, 1994). Pearce element ratios patterns related to fractionation and alteration in the H-W horizon and the Price formation andesite are examined below.

H-W horizon rhyolite units of the flow-dome complex

H-W horizon rhyolite units of the flow-dome complex (Figs. 3 and 4, Table 2; quartz porphyritic rhyolite, quartz-feldspar porphyritic rhyolite, green quartz-feldspar porphyritic rhyolite) progressively increase in feldspar and quartz concentration and become more coarsely crystalline as they decrease in age. This implies episodic emplacement from a crystallizing magma chamber. Varying proportions of feldspar and quartz in individual flow units suggest that primary igneous chemical variations probably are due to sorting of these two minerals (Table 1).

Fractionation of alkali feldspar in the H-W horizon rhyolite

![Fig. 17. Pearce element ratio diagram of Al/Zr versus (Na + K)/Zr (Pearce element ratios for H-W horizon rhyolite samples from the Battle zone, Buttle Lake mining camp. Least altered samples (labeled “F”, Table 2) plot along a line, given measurement error (2σ), with a unit slope. Thus, the compositional variation observed in these samples is consistent with alkali feldspar sorting that displaces rock compositions along a line with a unit slope in this diagram (Pearce, 1968; Russell and Nicholls, 1987; Stanley and Madeisky, 1994). Altered samples plot below this feldspar fractionation line because alteration (hydrolysis) has produced sericite (muscovite) from the feldspar in these rhyolites. Samples plotting on the sericite alteration line contain completely sericitized feldspar whereas those between this line and the feldspar fractionation line are only partially sericitized.](image-url)
Fig. 18. Pearce element ratio bubble-plot diagrams with Al/Zr Pearce element ratios versus (Na + K)/Zr Pearce element ratios for H-W horizon rhyolite samples (Fig. 17) from the Battle zone, Buttle Lake mining camp. Bubble sizes are proportional to Na/Zr (a), K/Zr (b), Fe/Zr (c), and Mg/Zr (d) Pearce element ratios values. Differences in the sizes of the bubbles reflect the amount of addition or loss that these elements have undergone. In the rhyolites, hydrolysis of alkali feldspar to sericite results in the loss of Na (a) and the addition of K (b). Iron (c) appears to have been added only to intensely sericitized rocks (cf. Stanley and Madeisky, 1994). Magnesium (d) appears to have been added to rocks that have less K, relative to Al, than would be expected in muscovite. This may be due to the formation of illite rather than muscovite.

Elements that have undergone material transfer in the H-W horizon rhyolite plot below the feldspar fractionation line in Figure 17. Al/Zr PER is the abscissa and (Na + K)/Zr PER is the ordinate. This diagram ignores the anorthite component of feldspar, which can be obscured by carbonate alteration. Since feldspar in the H-W rhyolite has the composition An_{22}Ab_{78} (Table 1) modeling just the alkali feldspar component accounts for most of the geochemical variation.

Loss of one mole of alkali feldspar from the melt causes one unit of proportional displacement each of Al/Zr PER and (Na + K)/Zr PER, thus in Figure 17, the melt composition is displaced down to the left along a line with the unit slope ("feldspar fractionation line"). Relatively fresh rocks from individual units of the H-W horizon rhyolite (QP, QFP, and GQFP, Table 2, labeled "F") plot on a line with the unit slope, which is consistent with the sorting of alkali feldspar (Pearce, 1968; Russell and Nicholls, 1988; Stanley and Madeisky, 1994). The most evolved (and youngest) samples plot to the lower left, suggesting evolution of cogenetic rhyolite units through the loss of feldspar crystals.

Altered samples of rhyolite plot below the feldspar fractionation line in Figure 17. All of these samples contain sericite (muscovite) that replaces feldspar phenocrysts and feldspar in the rock matrix. Samples that are completely sericitized plot on a line with a slope of one-third (the "sericite alteration line"). Partially sericitized rocks plot between the feldspar fractionation line and the sericite alteration line. The degree of sericitization a sample has undergone is quantified by the length of the vertical residual from the sample to the feldspar fractionation line. Qualitatively, rocks that plot close to the feldspar fractionation line are fresher than rocks that plot near the sericite line.

Elements that have undergone material transfer in the H-
TABLE 3. Major and Trace Element Geochemical Analyses for Representative Altered Rocks from the Battle Zone, Buttle Lake Mining Camp

<table>
<thead>
<tr>
<th>Unit</th>
<th>Sample no.</th>
<th>Section (E)</th>
<th>Drill hole</th>
<th>Depth (m)</th>
<th>Wt percent</th>
<th>Parts per million</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300W</td>
<td>15+85</td>
<td>14-906</td>
<td>309.9</td>
<td>62.80</td>
<td>96.62</td>
</tr>
<tr>
<td></td>
<td>50W</td>
<td>15+85</td>
<td>14-908</td>
<td>276.8</td>
<td>41.40</td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td>34W</td>
<td>15+85</td>
<td>14-914</td>
<td>262.5</td>
<td>96.62</td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td>32WR</td>
<td>15+85</td>
<td>14-914</td>
<td>254.3</td>
<td>60.50</td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td>220WR</td>
<td>13+72</td>
<td>14-918</td>
<td>246.2</td>
<td>86.87</td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td>104WR</td>
<td>17+98</td>
<td>14-918</td>
<td>257.5</td>
<td>36.44</td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td>103WR</td>
<td>17+98</td>
<td>14-918</td>
<td>276.5</td>
<td>72.84</td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td>204WR</td>
<td>17+98</td>
<td>14-918</td>
<td>272.3</td>
<td>85.96</td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td>160WR</td>
<td>17+98</td>
<td>14-918</td>
<td>223.5</td>
<td>66.48</td>
<td>6.59</td>
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<tr>
<td></td>
<td>17W</td>
<td>17+98</td>
<td>14-918</td>
<td>186.0</td>
<td>70.90</td>
<td>6.59</td>
</tr>
</tbody>
</table>


1 Wt percent
2 Parts per million
3 Units are spatially located in Figures 3 and 4
4 Price = Price formation andesite, PLT = pumiceous lapilli tuff, RTS = rhyolitic tuffaceous sediments, Mafic = H-W mafic sills, QP = quartz porphyritic rhyolite, QFP = quartz-feldspar porphyritic rhyolite, GQFP = green quartz-feldspar porphyritic rhyolite
5 Detailed location given in Robinson (1994)
6 L.O.I. = simple mass loss on ignition by heating, dl = below detection limit, blank = not analyzed
7 Analyzed in 1993 at Geochemical Laboratories, Earth and Planetary Sciences, McGill University, Montreal, Quebec; analytical details and associated errors are in Robinson (1994)
8 Analyzed in 1993 at Geochemical Laboratories, Earth and Planetary Sciences, McGill University, Montreal, Quebec; analytical details and associated errors are in Robinson (1994)

W horizon rhyolite are examined in Figure 18 (representative data for altered rocks are in Table 3). The sizes of bubbles in this figure are proportional to individual molar element ratios. Figure 18a and b indicates that sericitization of the H-W horizon rhyolite results in the loss of Na (Fig. 18a) and the addition of K, respectively. This pattern indicates that the H-W horizon rhyolite was originally a soda rhyolite (78% albite; Table 1) and that sericitization mainly occurred according to the following reaction:

\[ 3\text{NaAlSi_3O_8} + 2\text{H}^+ \rightarrow \]

KAl_3Si_5O_10(OH)_2 + 3Na^+ + 6SiO_2. (1)

where potassium was added to the rock, and sodium and silica were removed by the hydrothermal solutions. If K feldspar was the dominant alkali feldspar, sericitization would have resulted in a loss of potassium according to:

KAl_3Si_5O_10(OH)_2 + 2K^+ + 6SiO_2. (2)

and bubble sizes in Figure 18b would have become progressively smaller as alteration intensified toward the sericite alteration line.

Figure 18c and d examines the behavior of Fe and Mg, respectively, in the H-W rhyolite. These elements are commonly added to rocks during hydrothermal alteration associated with massive sulfide deposition (Large, 1992). Iron (as pyrite) only occurs in samples that have been intensely sericitized (Fig. 18c) and is an obvious indicator of hydrothermal
Fig. 19. Pearce element ratio diagram of Si/Zr Pearce element ratios versus (Al/2 + Fe + Mg + Ca + 5Na/2)/Zr Pearce element ratios to model fractionation in the least altered Price andesite samples (“F”) from the Battle zone, Buttle Lake mining camp. These samples plot on a line, given measurement error (2σ), with a unit slope. Thus, the compositional variation observed in these samples is consistent with plagioclase and pyroxene sorting, which displace rock compositions along a line with a unit slope (Pearce, 1968; Russell and Nicholls, 1988). The numerator coefficients in the ordinate (Si/Zr) of this plot model the fractionation of plagioclase, clinopyroxene, and orthopyroxene (the latter to accommodate the presence of subcalcic augite observed in these rocks; Stanley and Russell, 1989). Calcite addition or silicification (e.g., in veins) could contribute to the minor deviations of some samples from the fractionation line, as indicated by the labeled displacement vectors.

Price formation andesite

Price formation andesite consists of alternating feldspar and pyroxene + feldspar-porphryritic mafic to intermediate flows (Juras, 1987). Fractionation of plagioclase, clinopyroxene, and orthopyroxene (the latter to accommodate the presence of subcalcic augite observed in these rocks; cf. Stanley and Russell, 1989) is modeled in Figure 19, a plot of Si/Zr Pearce element ratios versus (Al/2 + Fe + Mg + Ca + 5Na/2)/Zr Pearce element ratios. The least altered samples (labeled “F”) mainly plot along a line with the unit slope. Minor deviation of two samples from the line may be from minor calcite addition or silicification (e.g., in veins).

Hydrothermal alteration is modeled in Figure 20 on a plot of Al/Zr Pearce element ratios versus 3K/Zr Pearce element ratios. This simpler diagram is used because the large number of elements in the ordinate numerator of the fractionation model of Figure 19 obscures discrimination of individual element additions and losses. Fractionation of plagioclase displaces rock compositions horizontally on this alteration diagram, but fractionation of pyroxene, regardless of composition, has no effect (Stanley and Russell, 1989). Hydrolysis of plagioclase to sericite, which displaces rock compositions upward to the sericite alteration line (slope = 1, due to the addition of K), results in the loss of Na (Fig. 20a) and Ca (Fig. 20b). Loss of Na most likely occurs by reaction 1, above. Loss of Ca most likely occurs according to:

\[ 3\text{CaAl}_2\text{Si}_2\text{O}_8 + 2\text{K}^+ + 4\text{H}^+ \rightarrow 2\text{KAl}_3\text{Si}_3\text{O}_{10}\text{(OH)}_2 + 3\text{Ca}^{2+}. \]

Iron has been added only to rocks that are intensely sericitized (Fig. 20c) and exhibits a behavior similar to iron addition in the H-W horizon rhyolite (Fig. 18c). Magnesium (Fig. 20d) has been lost in rocks that are completely sericitized (those rocks that plot along the sericite alteration line). However, Mg was added to those rocks that plot between the sericite alteration line and the abscissa. This chloritization occurred adjacent to feeder faults deep in the footwall (Fig. 21d).

Spatial distribution of alteration

Cross section 15 + 85E in Figure 21 (cf. Fig. 4b) presents the footwall and hanging-wall alteration patterns around the Battle Main lens. The bubbles in these diagrams have been scaled to the individual element ratio values and standardized to rock type.

Sodium and Ca losses define a broad halo around the ore deposit in both the H-W horizon rhyolite and Price formation andesite (Fig. 21a and b, respectively). Sodium is essentially absent in all rocks that have been intensely sericitized or chloritized. Large Ca bubbles (Fig. 21b) in the rhyolite hanging wall are due to the presence of either relatively fresh rhyolite or local calcite spherules and veins (Robinson, 1994). The core of the hydrothermal system is marked by significant Fe addition (Fig. 21c) as pyrite stringers and disseminations. Minor Mg addition in the footwall occurs in confined envelopes close to feeder faults in the footwall where chlorite occurs (Fig. 21d). In the hanging wall, Mg was added during low-temperature hydrothermal alteration possibly caused by the introduction of seawater reflected by the formation of Mg-bearing illite rather than muscovite. This zone of Mg addition spatially overlaps a zone of hematite alteration that also may have been produced by this seawater influx.

Concluding Interpretation of Battle Zone Geology, Alteration, and Mineralization

The following discusses the detailed evolution of the volcanostratigraphic sequence, alteration, and mineralization from the bottom to the top of the H-W horizon. Figure 22 schematically describes the major events from deposition of the Battle Main massive sulfide lens on the Price formation, through to emplacement of the rhyolite flow-dome complex. Evolution of the volcanostratigraphic sequence in the Battle zone is marked by a concomitant transition from chalcolphile Zn + Cu-type mineralization deposited in a synvolcanic rift basin.
(Battle Main lens) to felsic volcanism with accompanying lithophile Zn + Pb + Cu + Ba mineralization (Battle Upper lenses). Differences in metal and mineral assemblages between the different lens types are interpreted to be a result of water-rock reactions with a changing source rock. Major events are detailed below.

**Price formation andesite evolution and Battle Main massive sulfide lens deposition**

Price formation is a sequence of massive to pillow flows and associated breccias that was deposited subaqueously during a series of nonexplosive, effusive events. Subsequent riftting of the Price formation andesite formed the Butte Lake camp basin with minimum dimensions of 3 by 10 km. Block faulting within the basin was contemporaneous with the first cycle of sulfide deposition along the strike of the rift zone, represented by the Battle Main lens (Fig. 22a) and the correlative H-W Main lens (Fig. 2). Pyritic back argillite overlying the H-W Main lens suggests that the environment in the Battle Lake camp basin was probably quiescent and euxinic (Juras, 1987; Pearson, 1993).

The Battle Main massive sulfide lens is a large, tabular body from 130 to 210 m wide, 4 to 25 m thick, and at least 500 m in strike length. A sustained discharge of hydrothermal fluid was focused by symineral and synvolcanic feeder faults. The most significant feeder fault occurs at 4200 N (Fig. 4a and b) where it bounds a horst on the northeast margin of the Battle Main massive sulfide lens. Alteration close to this fault is characterized by quartz-sericite-pyrite with minor chlorite (Fig. 21). Diffuse discharge feeder stockworks below...
FIG. 21. Spatial distribution of Na/Zr (a), Ca/Zr (b), Fe/Zr (c), and Mg/Zr (d) Pearce element ratios on section 15 + 85E (Fig. 4b) through the Battle zone, Buttle Lake mining camp. The lower line approximates the contact between the Price formation andesite footwall and the H-W horizon rhyolite hanging wall of the deposit. Bubble sizes have been standardized within each lithology but are plotted together to illustrate the overall zonation of element additions and losses about the deposit. Sodium (a) and Ca (b) loss adjacent to the deposit, regardless of lithology, corresponds to sericitization. Iron (c) has been added mainly to the deposit's immediate footwall, where it occurs as pyrite. Magnesian addition (d) occurs within the footwall associated with chloritized andesite near feeder faults to the Battle Main lens, and in the hanging wall at the top of the rhyolite section. The latter may reflect Mg introduction from seawater during the hydrothermal alteration that formed illite.

much of the Battle Main lens lack chlorite. The principal alteration process is hydrolysis of plagioclase feldspar to sericite that resulted in a widespread loss of Na and Ca (Fig. 21a and b) but addition of K (reactions 1 and 3). Superimposed chloritization, important close to the main discharge site, is defined by a tightly confined Mg-addition anomaly (Fig. 21d).

Metals and minerals in the Battle Main massive sulfide lens are distinctly chalcophile. It is classified as a precious metal-enriched, Zn + Cu (sphalerite-pyrite-chalcopyrite)-type orebody (Robinson and Godwin, in prep.). This assemblage is typical of volcanogenic deposits underlain by andesite or basaltic andesite (Stanton, 1991). The Battle Main lens is zoned upward and outward from a laterally extensive footwall stringer zone in the Price formation andesite, through a core of massive pyrite and chalcopyrite, banded massive sulfide in the central region, to pale yellow massive sphalerite near the top and periphery, and local horizons of thin bedded sulfide at the top. The observed mineral zonation formed by a process we call “progressive zone replacement” such that early deposited exhalative sulfate and sulfide mud was replaced and recrystallized in response to reactions with upward and laterally migrating hydrothermal fluids (Robinson, 1994; Robinson and Godwin, in prep.; cf. Eldridge et al., 1983; and Ohmoto et al., 1983).

Onset of felsic volcanism

Fine rhyolitic tuffaceous and chert deposits represent the initial phreatoplinian outburst associated with the onset of
Fig. 22. Series of diagrams (not to scale) showing a depositional model for the H-W horizon in the Battle zone. The volcanic arc - remnant arc setting, established by Juras (1987), forms the basis for the diagrams. (a). Battle Main massive sulfide zone was deposited in fault-bounded basins within the Price formation andesite. Heated seawater (and possibly magmatic water) circulating through the volcanic pile discharged through synvolcanic (and synmineral) faults and reacted with cold sea water to deposit sulfide mud. The occurrence of a felsic magma chamber is inferred from the presence of rhyolitic volcanic deposits, but has not been intersected in drill core. Sulfide deposition was followed by phreatoplinian eruption from the volcanic arc and deposition of the fine rhyolitic tuffaceous deposits. Water suspension and turbidity currents deposited fine rhyolitic tuffaceous deposits that are commonly cherty due to post depositional silicification. (b). Generation of the pyroclastic flow, marked by deposition of the pumiceous lapilli tuff, reflects collapse of the eruption column. Crystals and lithics were sorted into the high-density part of the flow, and vitric material was winnowed into a convective column above the vent. Lower clouds of ash that rose above the moving pumice flows traveled across the water surface. Secondary steam explosions disrupted part of the flow when it entered the water. This was followed by water-settled suspension deposition of pumice blobs and accretionary lapilli that formed in the eruption column. (c). Collapse of the eruption column and deposition of the rhyolite tuffaceous sediments is marked by turbidity currents, water-settled suspension deposition, and possibly, debris flows. This was followed by deposition of Battle Upper massive sulfide lenses. (d). Eruption and extrusion of the felsic flow-dome complex from an underwater fissure ended the cycle of felsic volcanism.

felsic volcanism. Involvement of water at the volcanic edifice would have caused a high degree of fragmentation, thus ensuring the fine-grained nature of the deposits. In the Battle zone, the first felsic eruption followed deposition of the Battle Main lens but preceded mineralization in the Gap zone. Transport of ash to the Battle and Gap zones probably occurred via turbidity currents and gravitational settling of fine ash through the water column (Fig. 22b). The active hydrothermal system within and below the Battle Main massive sulfide lens would have discharged fluid into the felsic sediment pile and may have silicified much of the incoming sediment to cherty deposits. In the Gap zone, large-scale silicification was not significant.

Deposition of the Gap lens

Development of the hydrothermal discharge site that formed the Gap lens occurred about 200 m northeast and 50 m above the Battle Main massive sulfide lens (Fig. 4a). The
higher elevation of the Gap lens probably reflects a combination of the paleotopography of the Price andesite and basin fill with felsic pyroclastic rocks prior to deposition of the Gap lens (Fig. 22b). A feeder fault to the Gap lens has not been positively identified; however, the large size and strong metal and mineral zonation supports the existence of a focused, sustained discharge site for hydrothermal fluids. Diffuse discharge stockworks to the Gap lens have been identified in underlying Price andesite(?) and fine rhyolitic tuffaceous units.

Gap mineralization, intermediate between end-member types represented by the Battle Main (above) and Battle Upper lenses (below) is best described as Zn + Cu + Ba type (Robinson and Godwin, in prep.). The core of the lens is strongly pyritic and contains the ore minerals bornite, tennantite, anilite, colusite, and chalcopyrite. The uppermost or peripheral parts of the lens are rich in barite, sphalerite, and locally, galena. The association of barite, plus or minus galena, with deposits underlain by felsic rocks is compatible with the observation that the lithophile elements lead, barium, and potassium are more abundant in felsic rocks than in andesite. Deposits derived by leaching or from magmatic emanations of felsic rocks, therefore, are more likely to contain barite and galena. Further support for andesite versus felsic provenances for the different deposits comes from galena lead isotope studies by Godwin et al. (1996). They note that galena from deposits with discharge stockworks in andesite generally has a different lead isotope signatures than galena from mineralization with stockworks in felsic rocks.

Evolution of felsic volcaniclastic sequence: Subaqueous pyroclastic flow

The felsic volcaniclastic sequence in the Battle zone (Figs. 3 and 4) is composed of pumiceous lapilli tuff that is welded, rhyolite tuff with pumice blocks, and rhyolite tuffaceous sediments. This package is most simply explained as different components of one pyroclastic flow deposit (Fig. 22b and c). Although the origin of subaqueous pyroclastic flows is controversial, we suggest that the Battle zone volcaniclastics were generated from a subaerial edifice but were deposited subaqueously (cf. Sparks et al., 1980).

Pumiceous lapilli tuff has a number of unusual characteristics that support a subaerial pyroclastic origin: it is crystal rich compared to the rhyolite flows in the Battle zone; it contains cognate lithic fragments of quartz porphyritic rhyo-
lite rhyolite; it contains baked lithic and pyrrhotite fragments (Juras, 1986, 1987); and it has eutaxitic, welded textures. The first two characteristics are probably a result of mechanical sorting in an eruption column. Turbulence and convective circulation within the eruption column winnowed the fine portion of glassy ash into the upper part of the column while residually concentrating the crystals and lithic fragments at the base (Fig. 22b; Cas and Wright, 1988). The second two characteristics resulted from hot emplacement and associated welding. Once column collapse was initiated and material began to flow downslope, the relatively high density of the pyroclastic flow would have allowed it to maintain most of its integrity (and heat) upon entering the water. Baked accidental lithic fragments and pyrrhotite fragments entrained at the base of the flow are evidence for hot emplacement. Specifically, because pyrrhotite is not present in any of the massive sulfide deposits, Juras (1987) argued that it must have formed by thermal metamorphism of originally pyritic massive sulfide fragments. Formation of eutaxitic texture and welding occurred at the site of deposition.

Rhyolite tuff with pumice blocks was related to the same event. Pumiceous material that remained floating on the surface became water logged and were deposited by water suspension (Fig. 22b).

Rhyolite tuffaceous sediments (Figs. 3 and 22c), the uppermost component of the pyroclastic flow, has the following characteristics: it is crystal poor compared to cogenetic rhyolite flows and the pumiceous lapilli tuff, it contains small devitrified glassy fragments with local deposits of tube pumice, and it has accretionary lapilli deposits at the top. The crystal-poor nature reflects their derivation from the low-concentration vitric ash cloud that accompanied formation of the pumiceous lapilli tuff. Such a cloud would contain abundant volcanic products such as glass fragments and tube pumice and would provide an excellent environment for the formation of accretionary lapilli (Fig. 22c; McPhie et al., 1993). The presence of these lapilli supports our initial assumption that the eruption column was subaerial; there are no documented cases of accretionary lapilli actually forming in a submarine environment. The lapilli may, however, withstand a substantial degree of reworking by fluvial and marine processes (Boulter, 1987).
Deposition of Battle Upper massive sulfide lenses

Battle Upper massive sulfide lenses (Figs. 3, 4, and 22d) mark a hiatus between deposition of the rhyolite tuffaceous sediments and eruption of the rhyolite flow-dome complex. The sulfide lenses are relatively thin and discontinuous. Feeder zones to the massive sulfides are characterized by diffuse stockworks of polymetallic veins in sericitized rhyolite tuffaceous sediment. Hydrothermal fluids migrating upward through the base of the section were not channeled to specific discharge sites due to the lack of well-defined faults within the soft-sediment pile. As a result, alteration is widespread and less intense within the H-W horizon than in the Price andesite. The dominant alteration process was hydrolysis of oligoclase to sericite that resulted in a widespread loss of Na and Ca (Fig. 21a and b) and addition of K (reactions 1 and 3).

Metal and mineral assemblages in the Battle Upper lenses are distinctly lithophile compared to the Battle Main and Gap massive sulfide lenses. Robinson and Godwin (in prep.) classify these lenses as strongly precious metal-enriched Zn + Pb + Cu + Ba-type (sphalerite-tennantite-galena-barite) bodies. This is consistent with their occurrence within a felsic package. Larger lenses are zoned upward from basal polymetallic stringer mineralization in rhyolitic tuffaceous sediments, through tennantite-rich massive sulfide, to a barite-sphalerite blanket.

Emplacement of the rhyolite flow-dome complex

The rhyolite flow-dome complex (Figs. 3, 4, and 22d) represents a fissure eruptive system that is elongate northwest-southeast and thickens northeast. Thus, the inferred flow direction is southwest, with a vent source to the northeast. The exact location of the feeder is unknown.

Quartz porphyritic rhyolite intruded the Price formation andesite and basal rhyolite pyroclastics. It was a hot, shallow-level intrusion that marked the transition from explosive to effusive volcanism. Extrusion of the quartz-feldspar porphyritic rhyolite, followed by the green quartz-feldspar porphyritic rhyolite over the Battle Upper and Gap zones, ended the felsic eruptive cycle (Fig. 22d). Rubbly weathering, hematite alteration, and low-temperature alteration of rhyolite to Mg-bearing illite (Fig. 21d) suggest a period of exposure at the...
sea floor prior to the resumption of mafic volcanism and deposition of the hanging-wall andesite.

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REFERENCES


