THE BLUEBELL MINE
CENTRAL KOOTENAY ARC, SOUTH-EASTERN BRITISH COLUMBIA

by Kathryn Andrew

INTRODUCTION

The Bluebell mine is one of the major ore deposits in the lead-zinc terrain of British Columbia (Fyles, 1966), and is part of a larger metallogenic province extending south into Washington, Idaho and Montana. As one of the oldest mines in B.C. and a major producer in its time, the Bluebell mine provides us with a unique look at the geology and history of this part of southeastern B.C.

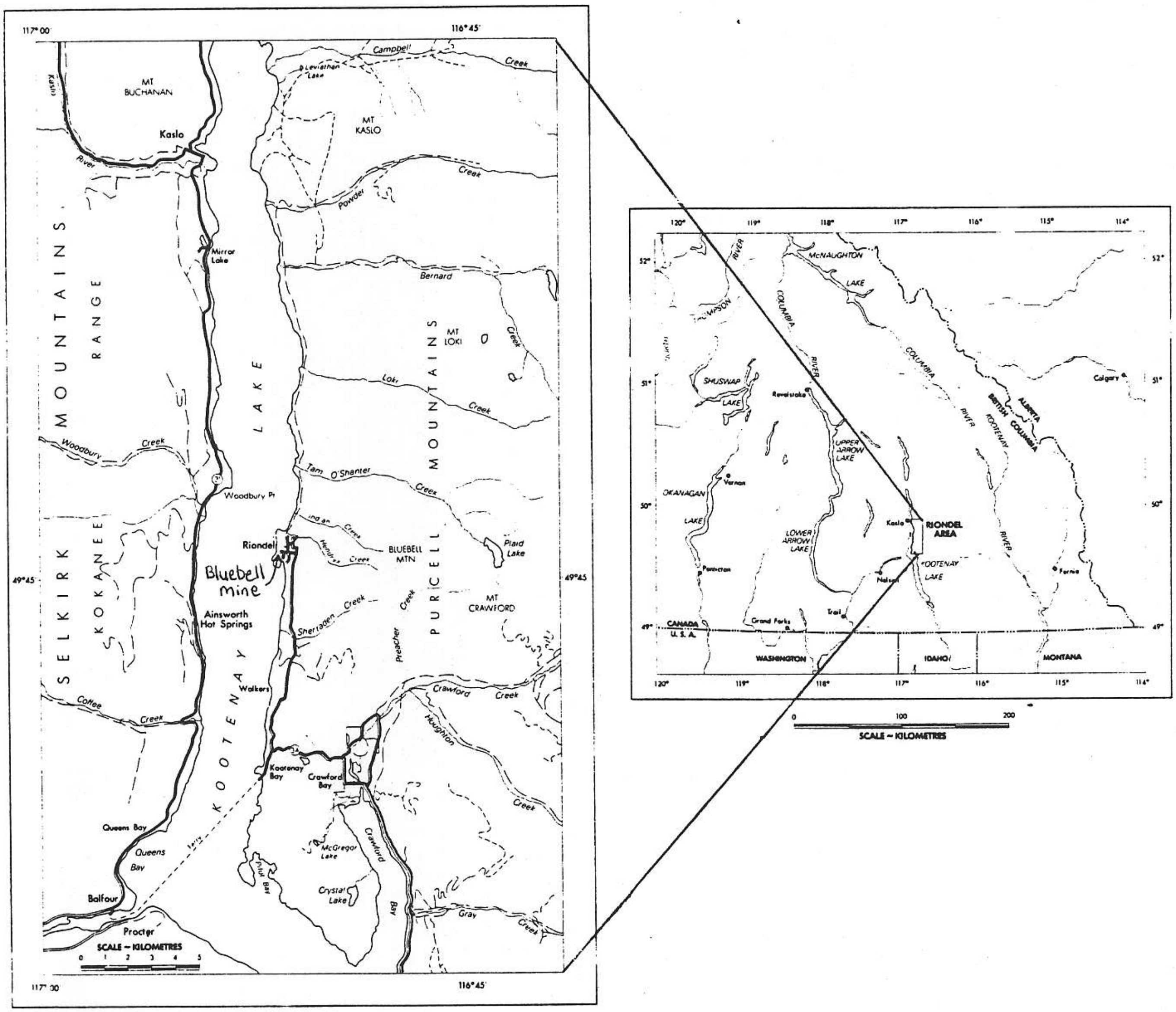


Figure 1. Location of the Bluebell Mine, Riondel Area, Southeastern British Columbia (from Hoy, 1980).

LOCATION AND ACCESS

The Bluebell mine is on the east shore of Kootenay Lake, 48km east of Nelson, in southeastern British Columbia. Access to the town of Riondel and the mine is by a 10km road which branches north from trans-provincial highway 3 along the Kootenay Lake shoreline (Fig. 1).

HISTORY OF EXPLORATION

Mineralized showings at the site of the Bluebell mine were first discovered in the early 1800s, but the property was not staked until 1882. Production from the Bluebell property began in 1895 and continued intermittently until 1927 under various owners. Ore was initially smelted at Pilot Bay, 12 km south of Riondel. During this time 491,000 tonnes of ore were mined averaging 6.5% Pb, 8.2% Zn and 96g/tonne Ag. Heavy flows of water in orebodies underlying Kootenay Lake caused a pumping problem which contributed to the closing of the mine. In 1927 Cominco acquired the property but little work was done until 1947. From 1952 to closure of the mine in 1971, Cominco Ltd. mined 4.333 million tonnes of ore averaging 5.1% Pb, 6.1% Zn, and 55g/tonne Ag. Total production was 4,823,000 tonnes containing 5.2% Pb, 6.3% Zn, and 60g/tonne Ag.

REGIONAL GEOLOGY

The Bluebell mine is located near the centre of the Kootenay Arc, a north trending arcuate structural zone in the south-eastern Canadian Cordillera (Hoy, 1977). To the east, the Kootenay Arc is flanked by older rocks of the Purcell Anticlinorium. The Shuswap Metamorphic Complex lies to the west (Fig. 2).

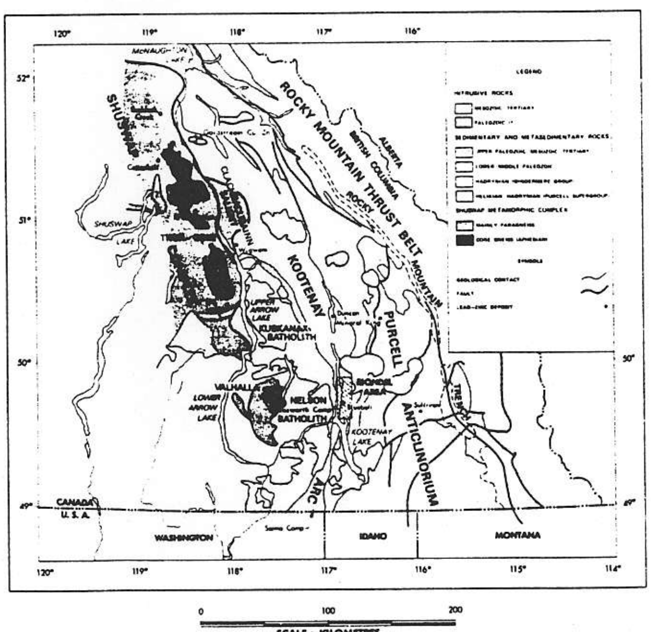


Figure 2. General geologic map of southeastern British Columbia (from Hoy, 1980).

The Bluebell mine lies within a local metamorphic culmination and near a regional stuctural culmination in the Kootenay Arc (Hoy, 1976 and 1977). Hadrynian to early Mesozoic rocks in this part of the Arc are compressed into isoclinal to tight, north-trending folds. To the north of the mine fold axes plunge gently northwards whereas to the south axes generally plunge south (Fyles and Eastwood, 1962, Fyles and Hewlett, 1959). Hoy (1977) draws attention to the existance of a major recumbent antiformal structure in this area called the Riondel nappe.

Regional metamorphic grade varies over the length of the Arc. The Salmo area is characterised by greenschist facies. Within the Riondel area, the metamorphic grade ranges from upper greenschist in the east to upper amphibolite in the west (Hoy, 1976). Metamorphic isograds trend north-south subparallel to the structural trend but are locally cross-cutting. Northward from Duncan Lake lower grade biotite and garnet zones predominate.

LOCAL GEOLOGY

Stratigraphy

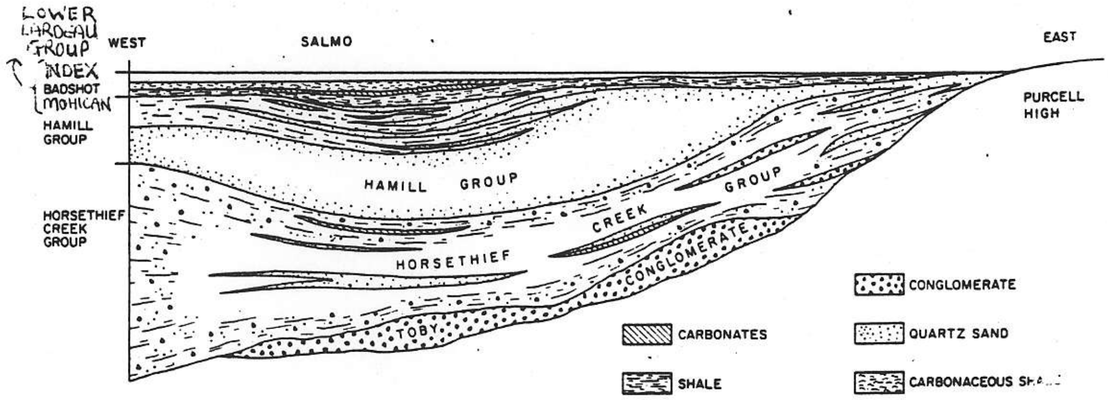
Rocks in the Bluebell mine have been correlated with a Lower Paleozoic sequence established in the Duncan Lake area to the north and Salmo area to the south (Hoy, 1980). The stratigraphic sequence for the Riondel area is illustrated in Table 1. Unfortunately, no fossils were found in the Riondel area so the sequence is based purely on correlation. This succession is inverted in the area of the Bluebell mine.

Table 1. Table of formations, Riondel area (from Hoy, 1980).

Group	Formation	Map Unit	Estimated Thickness *metres*	Description
Lardeau	Index	L4	top not exposed	micaceous schist and gneiss
		L3	400 – 450	calc-silicate gneiss, amphibolite, schist; impure marble; amphibolite layer and pure white quartzite layer near base
		L2	700	biotite-hornblende gneiss, amphibolite; minor calc-silicate gneiss, marble, and schist
		L1	150	micaceous schist
	Badshot	B	15 – 30	white crystalline calcite marble, dolomite
	Mohican	M	~50	interlayered quartzite, calcareous and micaceous schist, limestone, and dolomite
Hamill		H4	230	dark quartzite, dark fine-grained quartz-rich schist
		H3	60 – 200	massive, white quartzite
		H2	2 000	interbedded micaceous schist, quartzite, and siltstone; minor amphibolite
		H1	1 600	massive, white quartzite; gritty quartzite
Horse-thief Creek		HTC	base not exposed	fine-grained, light grey to green chlorite-muscovite schist and phyllite; rare white quartzite and marble near top

The oldest rocks in the area are the Horsethief Creek Group consisting mainly of chlorite-muscovite schist and phyllite with minor quartzite and marble. The lower Cambrian Hamill Group, overlying the Horsethief Creek Group, reaches a thickness of more than 3,500 metres in the mine area and is subdivided into four distinct units. The map units comprise quartzite, quartz-rich schist, micaceous schist and minor amphibolite. The lower Lardeau Group is subdivided into three formations as follows: the Mohican Formation, the Badshot Formation, and the Index Formation. The Mohican Formation, a gradational unit between the

Hamill Group and the Badshot marble, consists predominantly of thinly bedded calcareous schist and quartzite, rusty-weathering micaceous schist, and limestone. The Badshot Formation, correlative with the Reeves Formation in the Salmo camp, is the most distinctive marker unit in the sequence. In the mine area the predominantly pure limestone unit averages 15 to 30m in thickness. Irregular zones of dolomite and chert within the limestone host the lead-zinc deposits. Overlying the Badshot are several hundred metres of micaceous schist at the base of the Index Formation. Figure 3 illustrates a reconstructed section of Lower Cambrian rocks in the Kootenay Arc.



RESTORED SECTION LATE LOWER CAMBRIAN

Figure 3. Reconstructed section of Lower Cambrian rocks in the Kootenay Arc (after Fyles, 1970).

Three varieties of igneous rocks occur in the central Kootenay Lake area: 1) pegmatites, 2) granitic batholiths and related stocks, and 3)mafic dikes and sills. The most extensive pegmatite in the mine area is the hangingwall pegmatite. This laterally continuous sheet persists 1 to 10m below the hanging wall of the Badshot Formation (Fig. 4). Since intense regional metamorphism culminated during a phase 2 of deformation seen at the mine, many of the coarse grained bodies are in-situ metasomatic 'sweats'. Mobilization of these 'sweats' results in pegmatites that intrude the metasediments during various stages of phase 2 fold development. Major intrusions in the area include the Nelson batholith which lies 8km west of the mine and the Crawford stock situated 11km south of the mine. Where granitic rocks cut the major folds in the Kootenay Arc, thermal metamorphism is superimposed on pre-existing regional metamorphism (Muraro, 1966). A number of dark green to black mafic dikes and sills occur as the yougest phase of the igneous activities in the area (Rice, 1941). Two stages of extrusion are seen. Early lamprophyric dykes are broken into long segments by faulting along bedding planes within the Badshot Formation. Later diabase, greenstone and lamprophyric dykes cut both metasediments and pegmatites (Hoy, 1981).

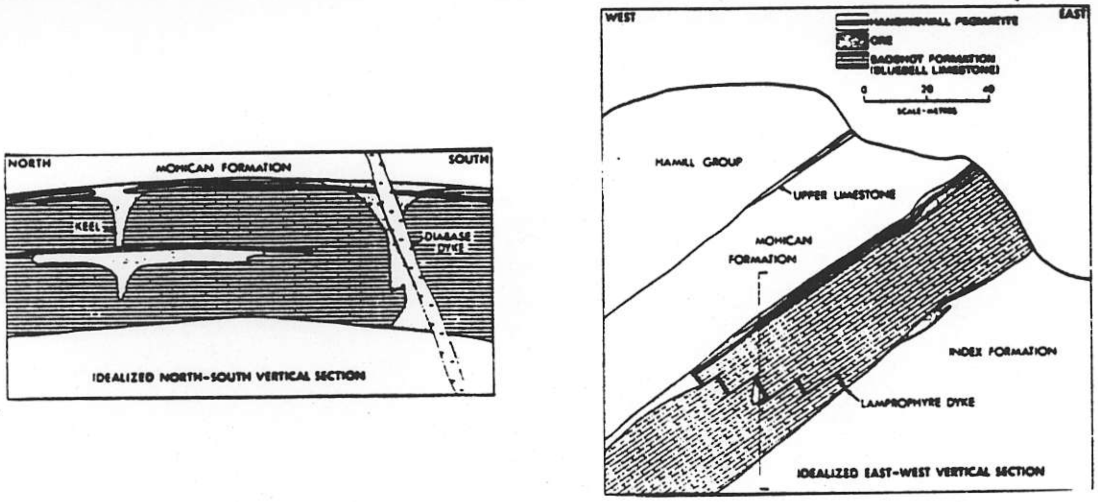


Figure 4. Idealized sections through the Bluebell Mine
(after Ransom, 1977).

Structure

The Riondel area is interpreted in terms of three phases of deformation by Hoy (1980). Phase 1 folding is documented by the stratigraphic section itself which is overturned and represents the lower limb of a large north trending westward-closing nappe, the Riondel nappe. Tight to isoclinal phase 2 folds are imposed on the Riondel nappe. These more open folds are also north trending with west-dipping axial surfaces. Southwest plunging, open phase 3 folding of earlier structures completes the deformation history (Hoy, 1981).

Two west-dipping reverse faults, the West Bernard and East Bernard faults, located 8km east of Bluebell mine, parallel the regional foliation (Fig. 7a). West of these faults, the stratigraphic section is inverted. However, to the east, the succession is right-side-up. Hoy (1980) divided the Riondel area into six structural domains each including one or more major phase 2 folds (Fig. 7a). The Bluebell mine lies within domain 2 which includes the hinge zone and limbs of the Crawford antiform, a phase 2 fold. Figure 5 is a composite section of the underlimb of

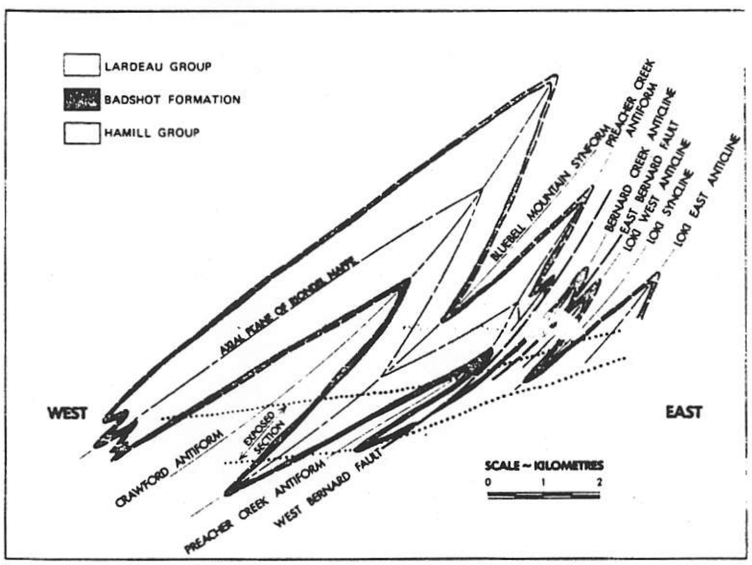


Figure 5. Composite section of the Riondel Nappe
(from Hoy, 1980)

the Riondel nappe taken from Hoy (1980) showing phase 2 structures developed in an inverted panel of Hamill, Badshot, and Lardeau rocks. The inverted limb of the Riondel nappe extends under Kootenay Lake to the west and is bounded to the east by the West Bernard fault. Hoy (1980) proposes two models to explain the development of the Riondel nappe. The first model assumes that the first and second phases of deformation are parts of one protracted deformational event (Fig. 6). The second model assumes that the Phase 1 folding which produces the Riondel nappe is separated by a finite time interval from the Phase 2 deformation of the nappe.

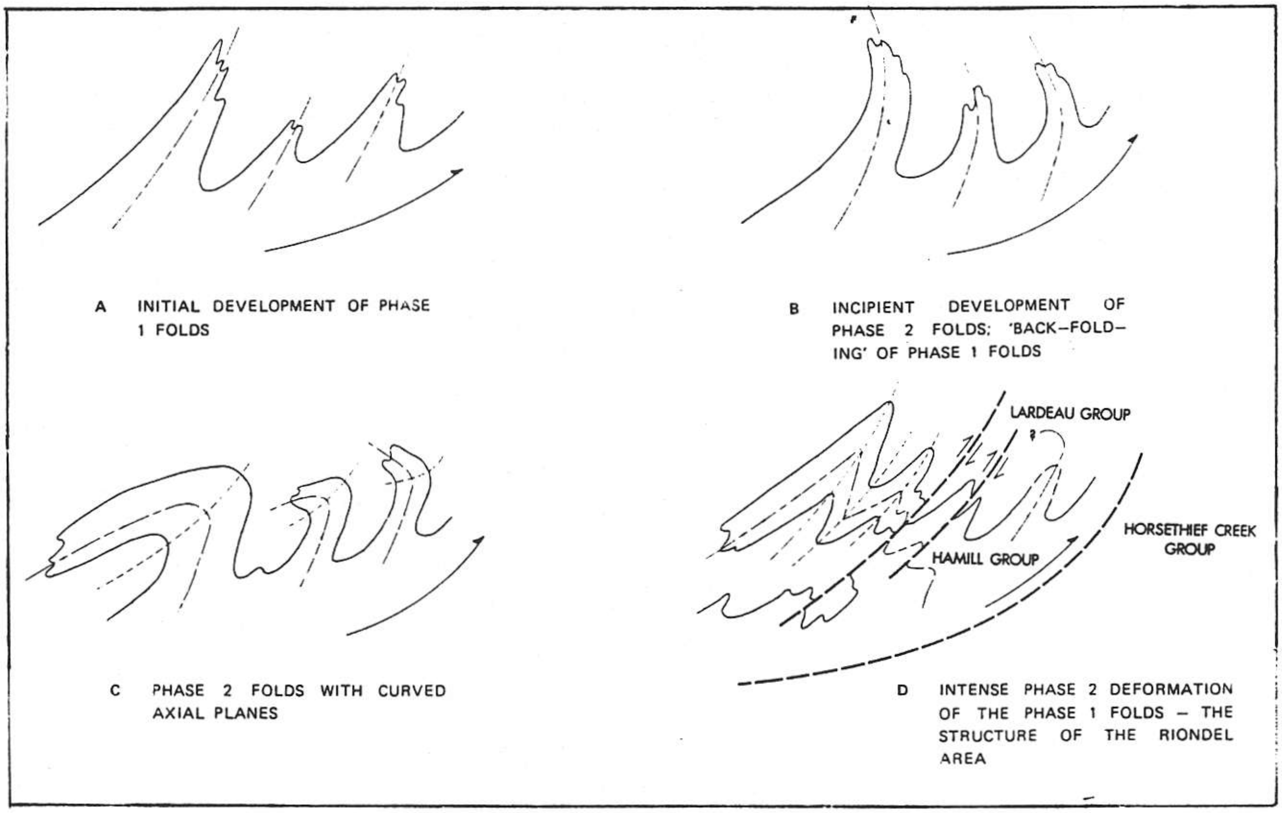


Figure 6. Postulated stages in the evolution of the Riondel nappe, assuming a model in which the first and second phases of deformation are parts of one protracted deformational event (after Hoy, 1980).

Metamorphism

Detailed studies of the Riondel area metamorphism have been carried out by Hoy (1976). The regional metamorphic grade in the Kootenay Arc ranges from lower greenschist to upper amphibolite facies. An elongate belt of silliminite grade metamorphism is centred on Kootenay Lake and extends north toward Duncan Lake. The Bluebell mine is located within this metamorphic culmination. Metamorphic grade ranges from upper greenschist facies in the east to upper amphibolite facies in the west within the Riondel area. Four calc-silicate isograds have been mapped in the Riondel area (Fig. 7b). These isograds trend northward subparallel to the dominant structural trends but are locally cross-cutting. Within the Riondel area two pelitic isograds (Fig. 7c) coincide on a P/T diagram defining pressure and temperature of metamorphism to be approximately 5.5kb and 625^{o}C (Hoy, 1980).

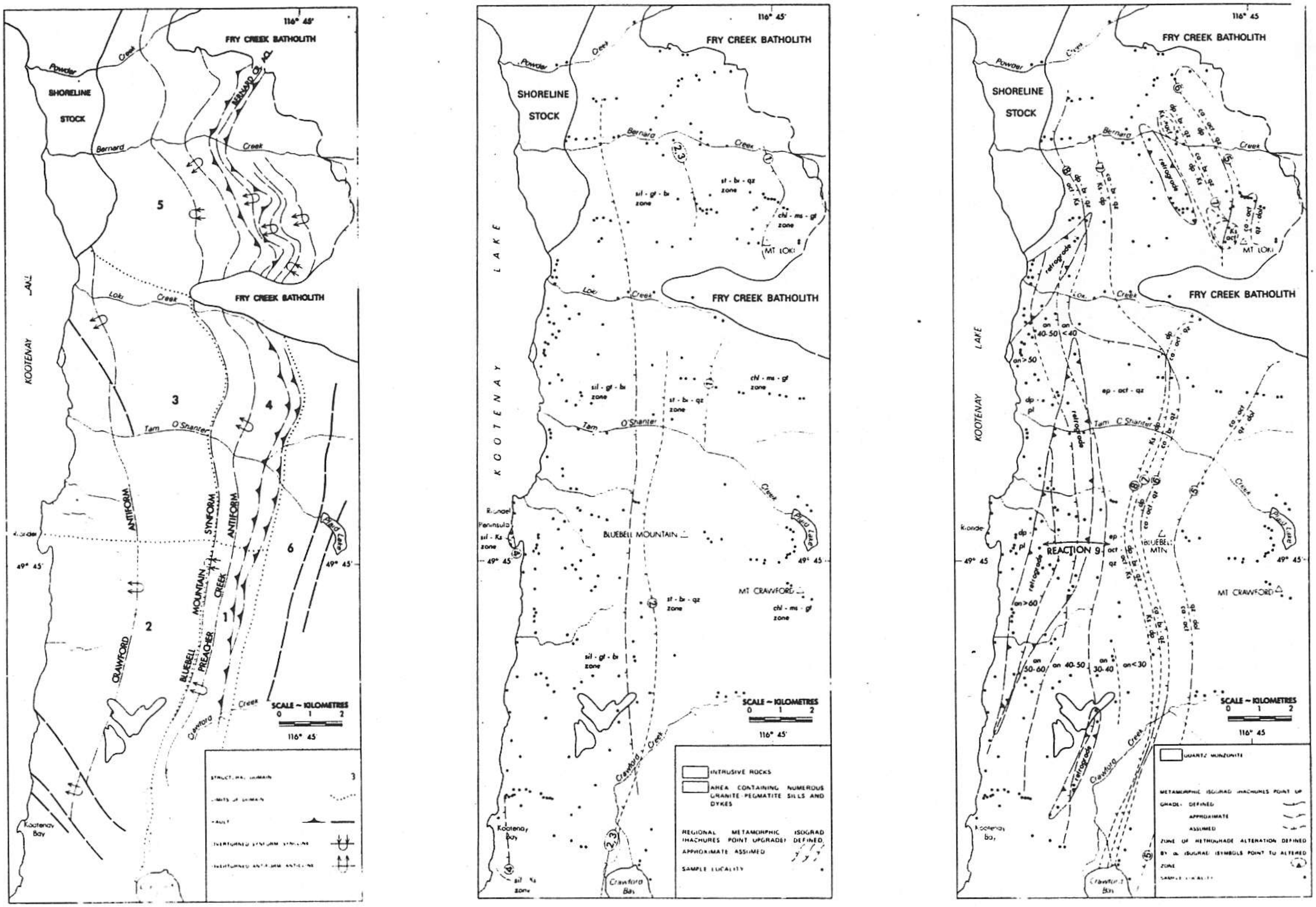


Figure 7. a) Structural domains in the Riondel area, b) Distribution of pelitic isograds and granite-pegmatite sills and dykes in the Riondel area, c) distribution of calc-silicate isograds in the Riondel area. Grade of regional metamorphism increases toward west (from Hoy, [illegible])

OREBODIES

The Bluebell mine is one of the major ore deposits in an important lead-zinc metallogenic province that extends from northern Idaho and Montana through southeastern B.C. to north of Revelstoke (Fyles, 1966). Shale-hosted, stratiform and stratabound carbonate hosted and lead-zinc-silver vein deposits occur in this area in a variety of rock types of various ages.

Lead-zinc deposits of the Kootenay Arc are divided according to Fyles (1966), into concordant and transgressive types on the basis of their structural relationships with host rocks. Concordant deposits are exemplified by Salmo-type deposits. Transgressive deposits are divided into two types: replacement deposits such as Bluebell and 'veins and lodes' typified by the Ainsworth Camp. Several lead-zinc silver vein occurrences are noted in the Riondel area. These may be related to a fracture system controlling late mineralization at Bluebell and in the Ainsworth Camp. Muraro (pers. comm. to Hoy, 1979) suggested that late fracture controlled mineralization may represent in-situ remobilization of an older stratabound deposit. Lead isotope data presented by Andrew et al. (1984) favours a syngenetic or penecontemporaneous origin and consequent Lower Cambrian age for the lead and mineralization. Such a model would require that karsting take place within the Badshot limestone and that the orebodies conform originally to the shape of pre-deformational karstic cavities.

The Bluebell ore deposits consist of three zones: the Comfort ore zone at the north end of the Bluebell peninsula, the Bluebell ore zone in the centre, and the Kootenay Chief ore zone at the south end (Fig. 8). Each of these zones is spaced at approximately 500 m

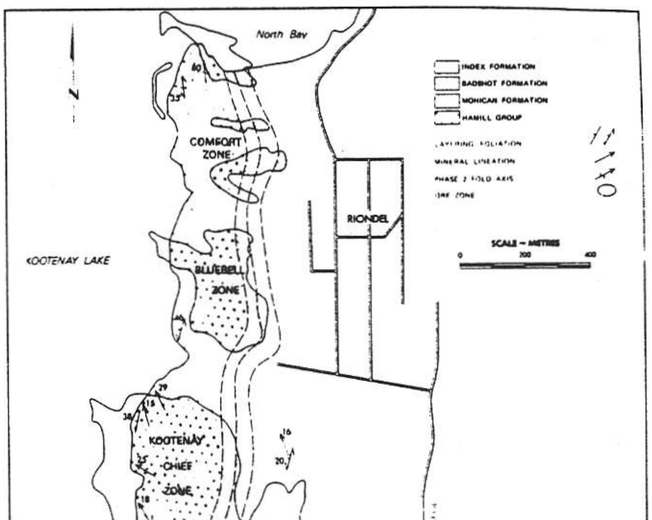


Figure 8. Sketch map of Riondel Peninsula showing distribution of formations and Bluebell ore zones, projected to surface (from Hoy, 1980).

intervals along the strike of the Badshot marble. The zones are localized along steep westerly trending cross-fractures and dip steeply to vertically north (Irvine, 1957). Figure 9 is a block diagram showing the mode of occurrence of the ore. Open phase 3 folding is seen in the east-west panel of the schematic diagram.

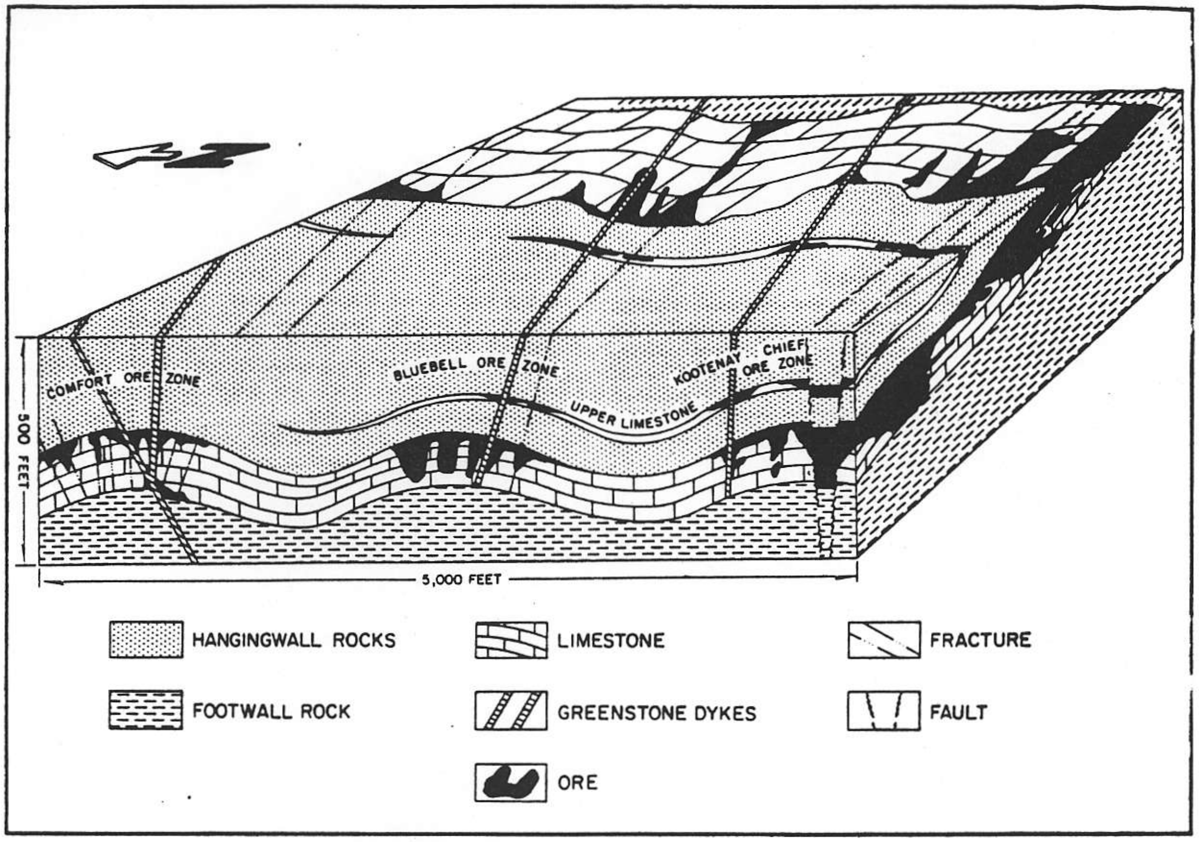


Figure 9. Block diagram of the Bluebell mine area showing mode of occurrence of the ore (from Shannon, 1970).

Ransom (1977) has described the geometry of individual ore shoots. His description follows (Reference to Figs. 10 and 11 is recommended):

"The ore shoots ranged in size from irregular pods of a few thousand tons to continuous masses of up to one million tons that extended down-dip as much as 500 metres. In cross-section, an average ore shoot was mushroom-shaped, the stem representing cross-cutting keels 1 to 30 metres wide and the cap representing a bedding-conformable horizon up to 6 metres thick that extended laterally as much as 50 metres from the keel zone. The keel zones extended below the conformable ore some 10 to 20 metres, narrowing and grading into a series of steep mineralized fractures that became uneconomical to mine. Some of the fracture zones and keel of the larger ore shoots extended to the footwall. A few ore shoots also developed along the footwall in a style complementary to hangingwall ore shoots. Depressions along the footwall and arches along the hangingwall were particularly favourable areas for ore accumulations. Ore shoots more than doubled in thickness and spread out laterally as 'runs' along strike on the down-dip side of displaced lamprophyre dyke segments. Very little ore occurred on the up-dip side of these segments and not until 30 metres further up-dip did ore attain normal thickness."

Structural controls on mineral distribution include steeply dipping cross-fractures, hangingwall Mohican Formation, footwall Index Formation, early lamprophyric dykes, pegmatite sills, joints (?), coarse-grained to fine-grained contacts and thin mud-filled fractures. Individual cross-fractures may have formed after karsting within the Badshot formation thus locallizing ore into "keel" zones. Figures 10 and 11 must be inverted to see the succession right-side-up. In this position, the Mohican Formation appears to act as an impermeable barrier channeling fluid movement through karstic cavities at the base of the Badshot Formation. The upper Index Formation provides a damning effect against which upwelling ore fluids are guided. Early lamprophyric dykes, displaced along bedding parallel fractures, act as local damns causing enrichment on the down-dip side and barren areas on the up-dip side of the dykes. Pegmatite sills form along structural weakness in ore shoots or bedding planes (Fig. 11D). Guiding of ore solutions laterally by thin mud-filled fractures and possible karsting of selected beds may explain tabular, bedding parallel shapes.

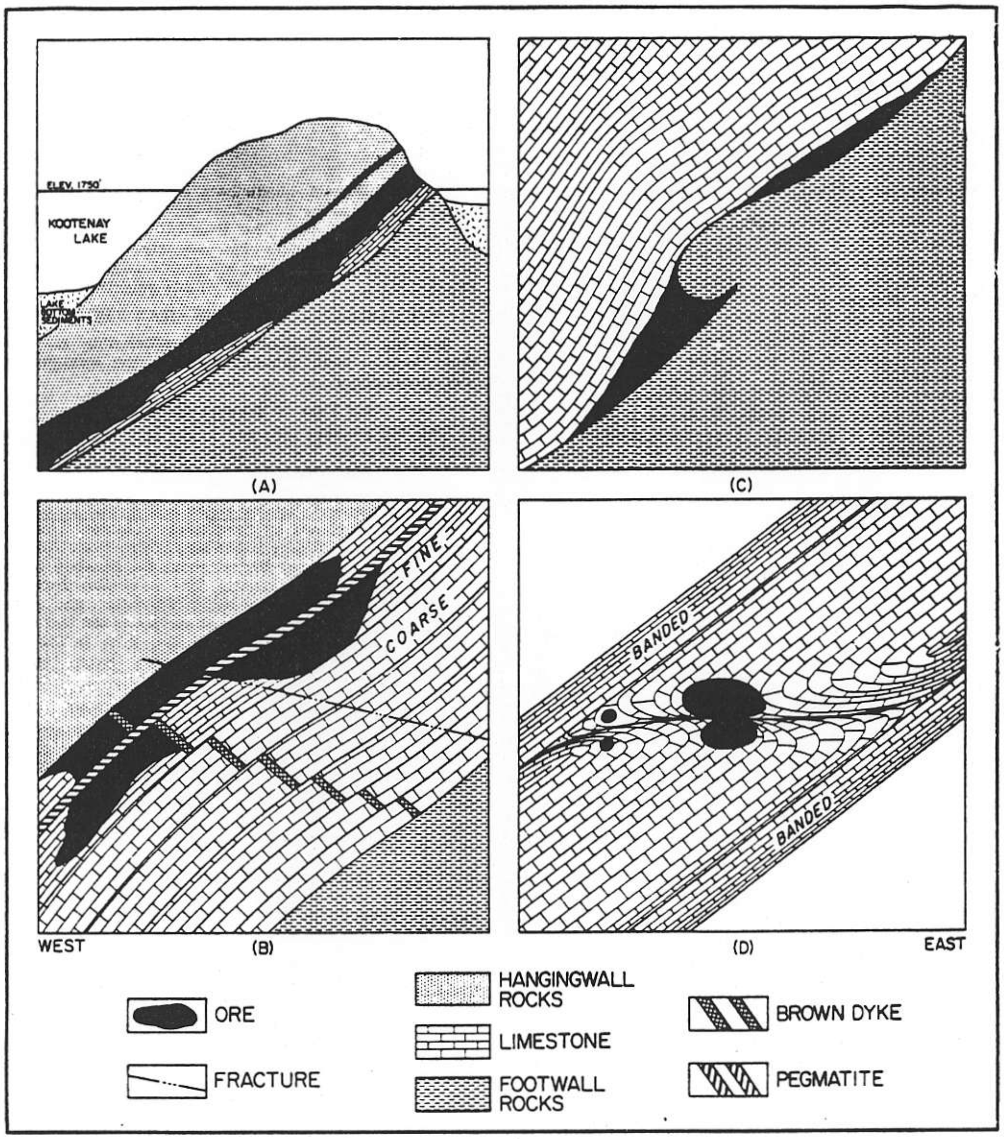


Figure 10. Diagrammatic cross-section showing A) a typical structural section in the Kootenay Chief Zone, B) displacement of a brown dyke and the occurrence of ore, C) and D) typical locations of ore bodies (from Shannon, 1970)

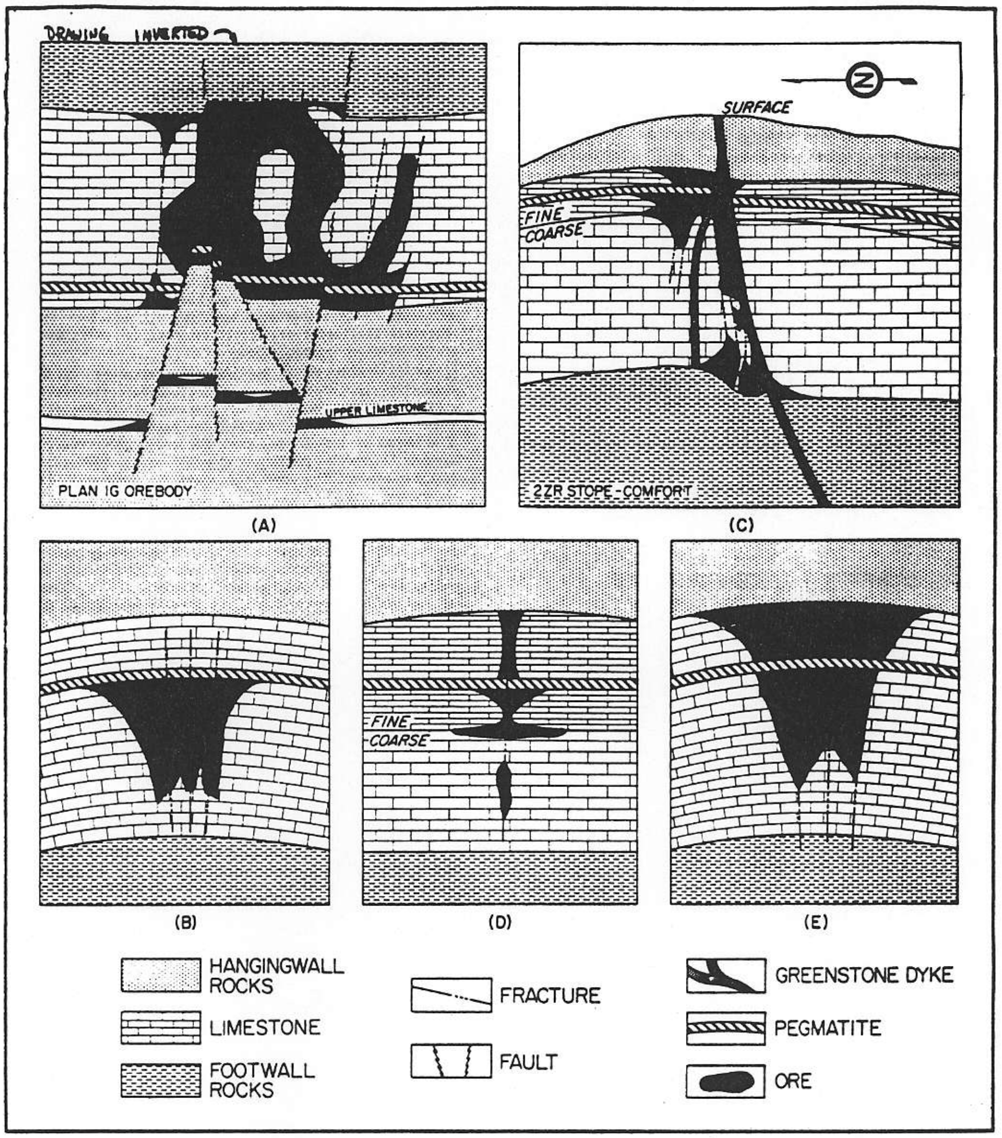


Figure 11. Diagrammatic plan (A) and longitudinal sections (B,C,D, and E) showing controls of mineralization. North arrow of C applies also to A,B,D, and E.

MINERALOGY AND PARAGENESIS

Over 90% of the hydrothermal minerals in the Bluebell mine occur as a replacement of limestone (Ohmoto, 1969). These replacement minerals are generally coarsely crystalline and massive consisting of sulphide minerals (pyrrhotite, sphalerite, galena, and minor arsenopyrite, chalcopyrite and pyrite), knebelite (Fe-Mn oli ·ıe), quartz and carbonates. Less than 10% of the mineralization is hosted in vugs. The hydrothermal mineralization may be subdivided into three episodes: 1) formation of knebelite, 2) deposition of massive sulphides, massive quartz and calcite, and 3) development of crystals in vugs (Ohmoto, 1969). The most common sphalerite in the Bluebell ores is marmatitic (high iron) sphalerite coexisting with pyrrhotite. Low-iron sphalerite is found in knebelite-rich areas occasionally associated with minor pyrite. The mineralogy of the Kootenay Chief ore zone is described in detail by Westervelt (1960) who identifies two types of mineralization refered to as the knebelite and siliceous zones. Sphalerite occurring either in coarse-grained masses or in veins is the most abundant sulphide in the knebelite zone. Galena, arsenopyrite, chalcopyrite and pyrrhotite are less common in this zone. The siliceous zone is characterized by abundant quartz and pyrrhotite, especially as well formed crystals in vugs.

Oxidation of the Bluebell ore occurred to depths greater than 300m (Shannon, 1970). The sequence of oxidation is: 1) alteration of pyrrhotite to lacy or spongy pyrite, 2) alteration of pyrite to hematite or limonite, and 3) oxidation of arsenopyrite, sphalerite and knebelite.

During early operation of Bluebell mine, CO_2 gas and CO_2-rich thermal water flowed from fissures encountered at depth. The water exceeded the pumping capacity of the mine, and produced various forms of carbonate deposits. A fluid inclusion study conducted by Ohmoto (1969) found that late fluid inclusions were also CO_2-rich.

ORIGIN

Structural and stratigraphic evidence at the Bluebell mine indicates that the deposits formed mainly as fracture controlled replacement bodies. Oreshoots are crosscutting and aligned with steep tensional cross-fractures. Sulphides are present both in the Badshot Formation and in the structurally overlying the Mohican Formation. Sulphides associated with quartz crystals in vugs suggests some deposition was late post-regional metamorphism and deformation.

Ohmoto and Rye (1970) studied the fluid inclusions and stable isotope geochemistry of the lead-zinc deposits. They consider the massive sphalerite-galena ores to be largely replacements of limestones at temperatures above 450°C. However, most of the published data concerns the late stage ore deposited in vugs at temperatures from 450°C down to 320°C. Salinity of the late fluids changed gradually from about 10wt.% eq. NaCl down to 3wt.% eq. NaCl. Essentially, the temperatures and salinities of fluids associated with earlier deposition of massive sulphide ores is unknown. If deposition of massive ores is related to karsting, temperatures should be low (50°C to 150°C) and salinities should be high, reflecting typical fluid inclusion data from carbonate-hosted deposits. The maximum pressure correction for the late stage fluids is less than 80°C. The P_{H2O} in the hydrothermal fluids was estimated to be in the range 300 to 800 atmospheres, and the depth of the ore deposition approximately 6km. The dO of the fluids during the vug stage changed gradually from +5 to -13 per mil as temperatures decreased (Fig. 12). During these progressive changes dD remained almost constant at -125 +/- 5 per mil. The dC composition of the fluids was also nearly uniform at -5.5 per mil suggesting a 'juvenille' origin of the carbon from graphite or limestone.

The nearly constant dD of the late-stage ore solutions is interpreted as indicating a dominantly meteoric origin for the water, with dO variations reflecting mixing of two meteoric waters, one of which had previously exchanged dO by reaction with high dO rocks at high temperatures.

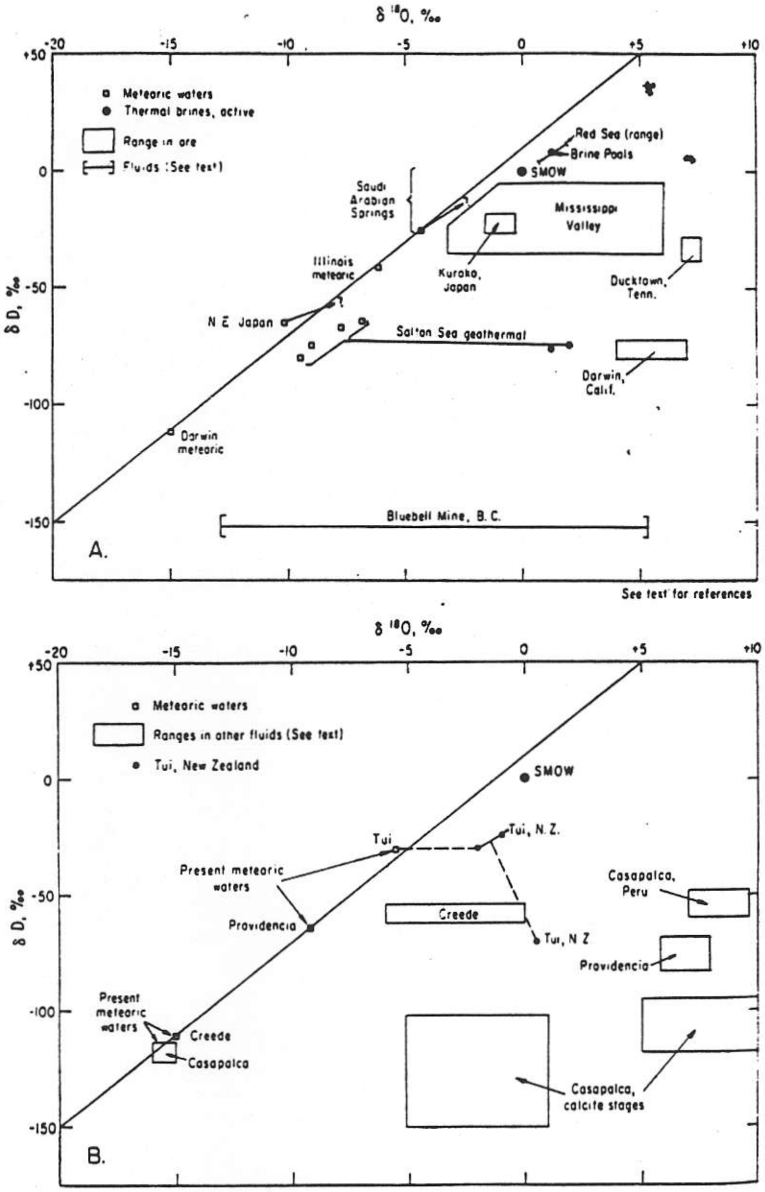


Figure 12. Isotopic compositions of waters of base metal deposits (from White, 1974)

Lead isotope data from the Kootenay Arc has been interpreted by several authors (Andrew et al., 1984; LeCouteur, 1973; Reynolds and Sinclair, 1971; Sinclair, 1964). Reynolds and Sinclair (1971) recognised two populations within the Kootenay arc: deposits to the far north and south of the Nelson batholith and deposits within and near the Nelson batholith. These populations coincide with the same geologically distinct 'concordant' and 'transgressive' deposits defined by Fyles (1966). Andrew et al. (1984) interpreted lead isotope data from the Kootenay Arc in terms of mixing line isochrons. The Bluebell limestone unit, correlated with the Lower Cambrian Badshot limestone, was used as a best estimate point of known age on which to construct a growth curve, the Bluebell curve, similar in concept to the shale curve constructed by Godwin and Sinclair (1982) (Fig. 13). The shale curve, developed primarily to describe lead evolution in the Selwyn shale basin, typifies lead

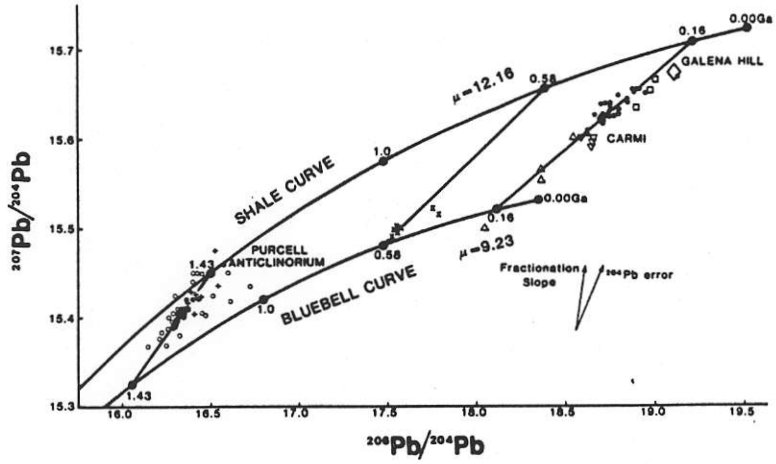


Figure 13. Plot of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ (from Andrew et al., 1984).

derived from upper crustal uranium-rich sources. The Bluebell curve typifies extremely unradiogenic lead derived from lower crustal or upper mantle, uranium-poor sources. Mixing line isochrons drawn between the growth curves at ages corresponding to the best estimates for mineralization ages in various camps within the Kootenay Arc closely fit the lead isotope data (Andrew et al.,1984).

EXPLORATION PARAMETERS

Bluebell-type mineralization is typified by mainly massive replacement of limestone in Lower Cambrian time with some late-stage Jurassic(?) fracture controlled mineralization in vugs and cavities. Orebodies take the shape of karstic cavities and related cross-fractures. Footwall and hangingwall rocks act as impermeable boundaries channelling fluid flow within the Badshot limestone. The area is characterised by post-mineralization polyphase deformation as well as post-mineralization high-grade thermal metamorphism superimposed on regional metamorphism. Lead from the Bluebell mine is anomalously low in $^{206}Pb/^{204}Pb$ and seems to reflect a uranium-depleted lead source from the lower crust or upper mantle. The location of this fundamental structure is unknown but it is suggested that Kootenay Lake itself may approximate the position of a deep-seated growth fault.

Exploration of the Reeves-Badshot unit along strike may uncover further mineralization similar to that of the Riondel area. Detailed geologic mapping in the Ainsworth Camp, west of Bluebell, may reveal similar replacement-type mineralization to that at Bluebell. Further lead isotope work in the Ainsworth Camp is also recommended to test similarities between Bluebell and Ainsworth lead. A regional look into the location of the upper limb of the Riondel nappe may disclose more Bluebell-type mineralization. Finally, a search for the elusive fundamental structure for unradiogenic lead, perhaps by galena lead analyses from small showings, may prove to be important in defining fundamental structures or zones related to Bluebell-type mineralization.

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