

# Carbonate-Hosted, Nonsulphide, Zinc-Lead Deposits in the Southern Kootenay Arc, British Columbia (NTS 082F/03)

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**KEYWORDS:** zinc deposit, nonsulfide, carbonate-hosted, hemimorphite, cerussite, oxide, Salmo district

## INTRODUCTION

Carbonate-hosted, nonsulphide, base-metal (CHNSBM) deposits are commonly overlooked during the selection of exploration targets. Under favourable geological, climatic, topographic and hydrological conditions, the weathering of a variety of carbonate-hosted, sulphide deposits may result in the formation of economically significant CHNSBM deposits. The primary objective of this paper is to provide conceptual background on CHNSBM deposits, supply concrete examples of direct-replacement, nonsulphide deposits from the Salmo district, British Columbia (NTS 082F/03) and demonstrate that the area has significant potential to host undiscovered wallrock-replacement-type CHNSBM deposits. The secondary objective is to explain the importance of deposit morphology and its spatial orientation in the preservation of such deposits within glaciated areas of southeastern BC.

## CARBONATE-HOSTED, NONSULPHIDE, BASE-METAL DEPOSITS

Nonsulphide deposits were the main source of zinc prior to the 1930s but following the development of differential flotation and breakthroughs in smelting technology, the mining industry turned its attention to sulphide ore. Today, most zinc is derived from sulphide ore (Hitzman et al., 2003). The situation, however, is changing as evidenced by the successful operation of a dedicated processing plant to extract zinc metal, through direct acid leaching, solid-liquid separation, solvent extraction and electrowinning, from nonsulphide and mixed ores mined at the Skorpion mine, Namibia. Geological information on CHNSBM deposits was reviewed by Hitzman et al. (2003). The CHNSBM deposits are interpreted to be of either supergene or hypogene origin (Hitzman et al., 2003; Sangster, 2003). The formation of supergene deposits is well established but

uncertainty remains regarding hypogene CHNSBM deposits.

In this paper, we concentrate on nonsulphide deposits formed in supergene environments from carbonate-hosted, sulphide, base-metal deposits (such as Mississippi Valley-type [MVT], sedimentary-exhalative [SEDEX], Irish-type or vein-type deposits and, to lesser extent, skarns). When carbonate-hosted, base-metal sulphide mineralization is subject to intense weathering, metals are liberated by the oxidation of sulphide minerals. The metals can be trapped locally, forming direct-replacement, nonsulphide, ore deposits (Heyl and Bozion, 1962; Hitzman et al., 2003) also referred to as “residual” ore by Reichert and Borg (2008).

A schematic section of an idealized direct-replacement deposit is shown in Figure 1a. During the formation of a direct-replacement CHNSBM deposit, primary ore (protore) is oxidized, and base metals pass into solution and are redistributed and trapped within space originally occupied by the protore. Depending on the extent of replacement of the sulphides by base-metal and iron-bearing nonsulphide minerals (oxides, silicates, carbonates and phosphates), the resulting ore is called mixed (combination of sulphide and nonsulphide ore) or nonsulphide ore (also referred to as oxide ore). If the base metals liberated by the oxidation of sulphide ore are not trapped locally, they are transported by percolating waters down and away from the sulphide protore and may form wallrock-replacement CHNSBM deposits (Figure 1b). Wallrock-replacement deposits can be located in proximity to protore or several hundreds of metres away (Heyl and Bozion, 1962; Hitzman et al., 2003; Reichert and Borg, 2008). Alternatively, if the metal-bearing solutions do not encounter conditions favourable for trapping within nonsulphide minerals (by direct- or wallrock-replacement processes), metals are dispersed in low concentration over large areas (i.e., without forming economic ore deposits).

Heyl and Bozion (1962) and Hitzman et al. (2003) also described residual and karst-fill, supergene, nonsulphide, base-metal deposits formed by mechanical or chemical transport followed by accumulation of previously formed nonsulphide mineralization in karst depressions and underground systems. These deposits are typically high grade and small tonnage. We do not discuss these deposit types here. The main nonsulphide Zn-, Pb- and Fe-bearing minerals and their characteristics are listed in Table 1. The reader is referred to Hitzman et al. (2003) for a more complete list.

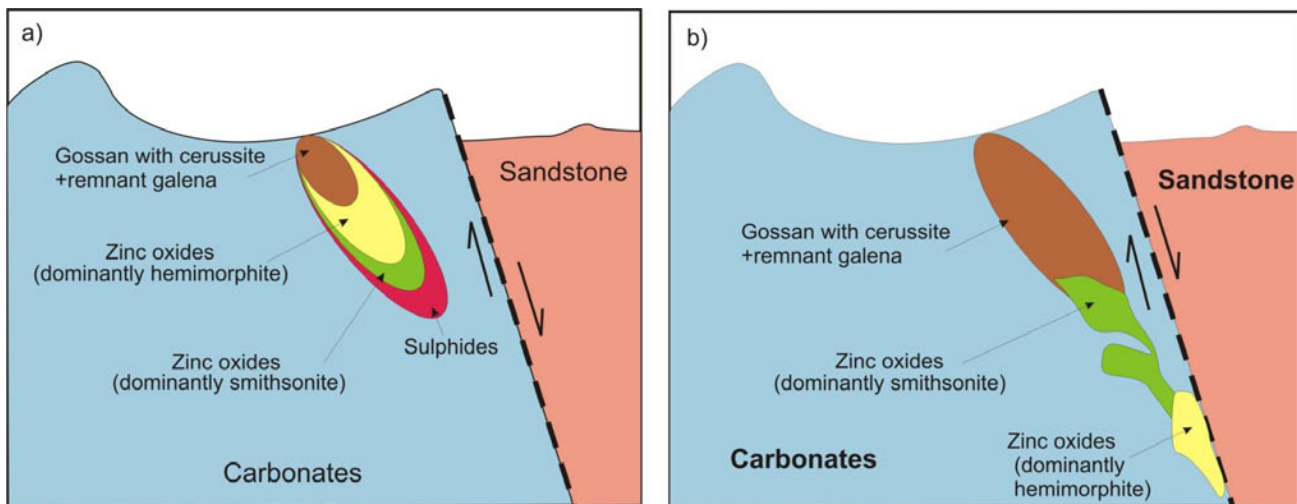
Historically, most CHNSBM deposits were thought to be small; some deposits and districts, however, have tonnage comparable to world-class sulphide deposits, especially if mixed ores are also considered (Figure 2). The Balmat deposit (New York), which is a large stratiform, carbonate-hosted, Zn sulphide deposit, is shown for comparison. The Balmat deposit has a near-surface

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**Figure 1.** Idealized sections of carbonate-hosted, nonsulphide, base-metal deposits: a) direct-replacement deposit; b) wallrock-replacement deposit (modified from Heyl and Bozion, 1962; Hitzman et al., 2003).

nonsulphide component of <100 000 tonnes at 10–29% Zn (too small to show on Figure 2). Skorpion (Namibia), which has 60 million tonnes of mixed resource grading 6–8% Zn and 1–2% Pb and 24.6 million tonnes of oxide resource grading 10.6% Zn, and Mapimi (Mexico), which has 6 million tonnes at 15% Zn, 10% Pb and 500 g/t Ag, are examples of large, high-grade, nonsulphide deposits (Corrans et al., 1993; Titley, 1993).

A summary of Zn and Pb grades of major CHNSBM deposits is presented in Figure 3. Where the data are available, the Pb and Zn content of sulphide protore and mixed (nonsulphide and sulphide) ores that are genetically related to CHNSBM mineralization are also shown. CHNSBM mineralization has higher Zn and lower Pb content than mixed ore and/or the sulphide protore (Figure 3) from which it was derived. Wallrock-replacement deposits are commonly rich in Zn and poor in Pb relative to the direct-replacement CHNSBM deposits.

The above summary is an oversimplification. The oxidation of base-metal ore is commonly a multicyclic process (Hitzman et al., 2003). Diversity in the type of protore, and the multicyclic nature and variations in near-surface geological processes result in a wide spectrum of CHNSBM ores. Reichert and Borg (2008) proposed two extremes of CHNSBM ores, “red ores” and “white ores”. Red ores consist commonly of Fe-oxyhydroxides, goethite, hematite, hemimorphite, smithsonite, hydrozincite and cerussite. They typically contain >20% Zn, >7% Fe and Pb±As. White ores, consisting commonly of smithsonite, hydrozincite and minor Fe-hydroxides, contain <40% Zn, <7% Fe and very low concentrations of Pb. The stability of hemimorphite is largely dictated by the activity of silica within the system. Hemimorphite may be present within red or white ores. Red ores are found largely in the settings where the direct-replacement process (Figure 1a), as defined by Hitzman et al. (2003), predominates. White ore, at the opposite end of the spectrum, may be found as replacement of breccia clasts and wallrock or as breccia cement or open-space filling. It may be located tens to several hundreds of metres from the nearest sulphide ore, mixed ore, red ore or gossan. From metallurgical and environmental considerations, white ores are simpler and preferable.

## REGIONAL GEOLOGY

The area of interest is located in the Kootenay Arc of southeastern BC (Figure 4). The Kootenay Arc is an arcuate belt of complexly deformed rocks extending at least 400 km from near Revelstoke to the southwest across the Canada–United States border (Fyles, 1964). The Kootenay Arc lies between the Purcell Anticlinorium in the Purcell Mountains to the east and the Monashee metamorphic complex to the west (Figure 4). The Arc consists of a thick succession of thrust-imbricated Proterozoic to Lower Mesozoic miogeoclinal to basinal strata of sedimentary and volcanic protoliths (Brown et al., 1981).

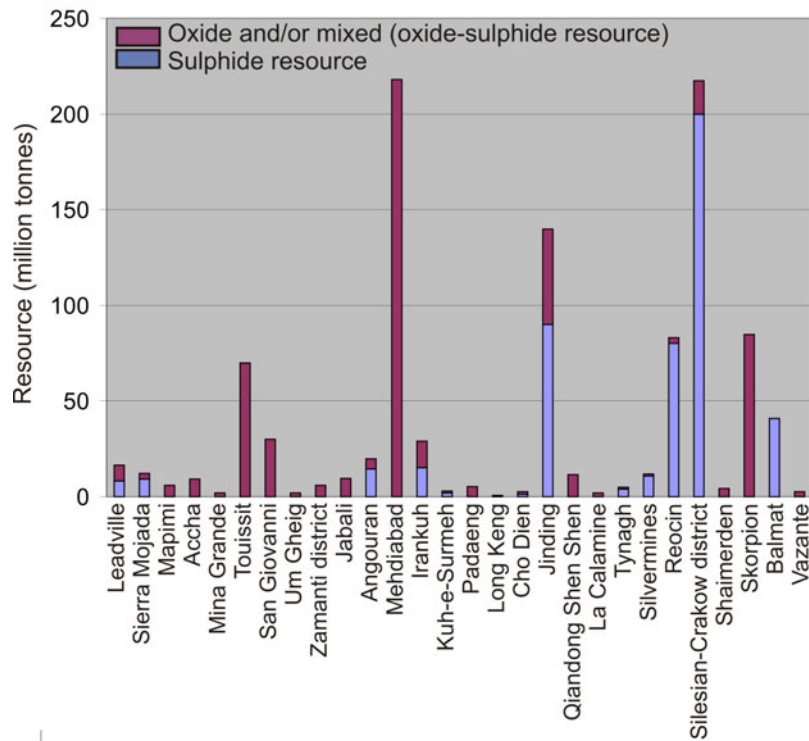
Colpron and Price (1995) outlined a regionally coherent stratigraphic succession in the Kootenay Arc. The lower part is composed of siliciclastic and carbonate rocks of the Eocambrian Hamill Group and Mohican Formation. These are overlain by the archaeocyathid-bearing carbonate rocks of the Lower Cambrian Badshot Formation and its equivalent, the Reeves Member of the Laib Formation (Fyles and Eastwood, 1962; Fyles, 1964; Read and Wheeler, 1976), which host a number of Zn–Pb sulphide deposits. The Badshot Formation is characterized by calcitic dolomitic marble. Schist is locally interlayered with the marble. In the southern part of the Kootenay Arc, the carbonate rocks are overlain by siliciclastic, basinal shale and mafic volcanic rocks of the Lower Paleozoic Lardeau Group (Colpron and Price, 1995). Polyphase deformation has transposed bedding and locally obscured primary stratigraphic relationships (Colpron and Price, 1995).

## GEOLOGICAL SETTING OF THE CARBONATE-HOSTED SULPHIDE DEPOSITS

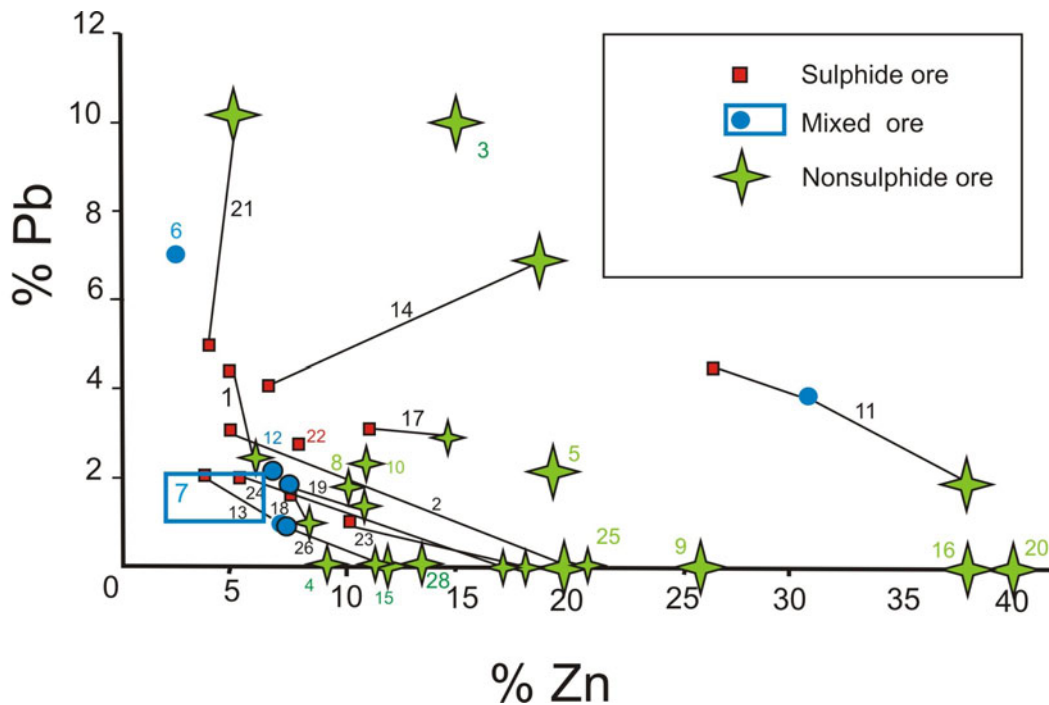
The Kootenay Arc hosts numerous carbonate-hosted Zn–Pb deposits (Höy, 1982; Nelson, 1991). The carbonate-hosted Zn–Pb deposits are distributed along the Kootenay Arc. The main concentrations define the Salmo and Duncan camps in southern BC. Smaller deposits characterize the northern part of the Kootenay Arc (Figure 4). The deposits, commonly referred to as “Kootenay Arc-type de-

**Table 1.** Selected nonsulphide Zn-, Pb- and Fe-bearing minerals and their characteristics.

	<b>Formula</b>	<b>Colour</b>	<b>Lustre</b>	<b>Density</b>	<b>Hardness</b>	<b>Comments</b>
<b>Main Zn-bearing minerals</b>						
Smithsonite	ZnCO <sub>3</sub>	white	earthy, dull	4.5	4.4	soluble in HCl, botroidal, reniform, earthy or granular; may be fluorescent, greenish or bluish or whitish in ultraviolet light
Hemimorphite	Zn <sub>4</sub> Si <sub>2</sub> O <sub>7</sub> (OH) <sub>2</sub> ·H <sub>2</sub> O	white, brown, greenish grey	vitreous	3.6	5	weakly soluble in HCl, massive, botroidal, stalactitic
Hydrozincite	Zn(CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>6</sub>	white, pale yellow, pale grey	pearly	3.6–3.8	2–2.5	massive, fibrous, bladed aggregates; fluorescent pale blue or lilac in ultraviolet light; soluble in acids and amonia
Sauconite	Na <sub>0.2</sub> Zn <sub>3</sub> Si <sub>3</sub> AlO <sub>10</sub> (OH) <sub>2</sub> ·4(H <sub>2</sub> O)	white, pale brown, reddish brown	dull, earthy	2.45 (variable)	1.0–2.0	earthy, clay-like texture
Willemite	ZnSiO <sub>4</sub>	white, green, red, brown, black, pinkish, bluish	vitreous/resinous	3.9–4.2	5.5	massive, granular, prismatic; fluorescent green in short ultraviolet light
Zn-bearing aragonite	(Zn,Ca)CO <sub>3</sub>	white, grey, yellowish	vitreous	3	3.5–4.0	fluorescent green in short ultraviolet light; effervesces in HCl; fibrous, prismatic, columnar
Minrecordite	CaZn(CO <sub>3</sub> ) <sub>2</sub>	white to colourless, brown, blue-green	vitreous to pearly	3.5	3.5–4	rhombohedral, sometimes saddle-shaped
<b>Main Pb-bearing minerals</b>						
Cerussite	PbCO <sub>3</sub>	colourless, white, tan, grey	adamantin	6	3	massive granular, reticulate, well-formed prisms; fluorescent yellow in long wave ultraviolet light
Anglesite	PbSO <sub>4</sub>	white, colourless, grey, bluish, yellow	vitreous to adamantin	6.3	3–3.5	granular, anhedral to subhedral crystals; commonly fluorescent yellow in ultraviolet light
Pyromorphite	Pb <sub>5</sub> (PO <sub>4</sub> ,AsO <sub>4</sub> ) <sub>3</sub> Cl	green, brown, yellow	resinous to adamantin	6.7–7	4	prismatic or reniform and globular textures
Plumbojarosite	PbFe <sub>6</sub> (SO <sub>4</sub> ) <sub>4</sub> (OH) <sub>12</sub>	golden to dark brown	vitreous to dull	3.6	1.5–2.0	soluble in HCl, earthy, concretionary, encrustations, lumps
Litharge	PbO	red	greasy	9.14–9.3	2	encrustations
Mimetite	Pb <sub>5</sub> (AsO <sub>4</sub> ,PO <sub>4</sub> ) <sub>3</sub> Cl	brown, yellow, tan, brown, white	resinous	7.1–7.3	3.5–4	reniform, globular, sometimes prismatic
<b>Main Fe-bearing minerals</b>						
Goethite	FeO(OH)	dark or rusty brown, black	dull, resinous	4–4.4	3.5–4	earthy, botroidal, stalactitic
Hematite	Fe <sub>2</sub> O <sub>3</sub>	red to nearly black	typically dull	5.2	5	coatings, stains, fracture fillings



**Figure 2.** Tonnages of selected carbonate-hosted, nonsulphide, base-metal deposits, associated nonoxidized sulphide protore and mixed ores (based on compilation of Hitzman et al., 2003).



**Figure 3.** Zinc and lead grades of carbonate-hosted, nonsulphide, base-metal (CHNSBM) deposits. Where data are available, Pb and Zn content of genetically related, sulphide protore and mixed (nonsulphide and sulphide) ore are connected by a tie line. In most cases, CHNSBM ore has higher Zn content than related mixed ore and nonoxidized sulphide protore (based on compilation of Hitzman et al., 2003). 1. Leadville (U.S.A.), 2. Sierra Mojada (Mexico), 3. Mapimi (Mexico), 4. Accha (Peru), 5. Mina Grande (Peru), 6. Touissit (Morocco), 7. San Giovanni (Italy), 8. Um Gheig (Egypt), 9. Zamanti district (Turkey), 10. Jabali (Yemen), 11. Augouran (Iran), 12. Mehdiabad (Iran), 13. Irankuh (Iran), 14. Kuh-e-Surmeh (Iran), 15. Padaeng (Thailand), 16. Long Keng (Myanmar), 17. Cho Dien (Vietnam), 18. Jinding (China), 19. Qiangdong Shen Shen (China), 20. La Calamine (Belgium), 21. Tynagh (Ireland), 22. Silvermines (Ireland), 23. Reocin (Spain), 24. Silesian-Crakov district (Poland), 25. Shaimerden (Kazakhstan), 26. Skorpion (Namibia), 27. Balmat (U.S.A.), 28. Vazante (Brazil). All deposits, with the exception of Vazante, are considered supergene in origin.

posits” (Höy, 1982; Nelson, 1991), occur in the Badshot Formation or its equivalent, the Laib Formation (Reeves Member). They are interpreted to be metamorphosed Mississippi Valley-type or Irish-type Pb-Zn deposits (Paradis, 2007, 2008). They range in size from 6 to 10 million tonnes with average grades of 3–4% Zn, 1–2% Pb, 0.4% Cd and traces of Ag (Höy, 1982; Höy and Brown, 2000). They are stratabound and stratiform lens-shaped concentrations of sulphides (sphalerite, galena, pyrite, local pyrrhotite and rare arsenopyrite) in isoclinally folded dolomitized or silicified carbonate layers (Paradis, 2007). Several deposits are past-producers (e.g., Reeves MacDonald, Jersey, HB, Bluebell) and others have seen advanced exploration work (e.g., Duncan, Wigwam), although none are presently in production.

## CARBONATE-HOSTED SULPHIDE DEPOSITS OF THE SALMO CAMP

The Salmo camp comprises numerous carbonate-hosted Zn-Pb deposits. With the exception of Lomond and

Caviar (which are hosted by the Cambrian Nelway Formation), the deposits are hosted by fine-grained, poorly layered or massive dolomite of the Reeves Member, which is texturally distinct from barren, generally medium-grained, well-banded, grey and white or black and white limestone of the same unit. The mineralized dolomite is dark grey, poorly layered and mottled with black flecks, wisps and layers of impurities (Fyles, 1970). The deposits, their dolomitic envelopes, and the limestone hostrock generally lie within secondary isoclinal folds along the limbs of regional anticlinal structures. They form stratiform, tabular and lens-shaped concentrations of pyrite, sphalerite and galena in dolomitized zones. Brecciated zones are common within the more massive sulphide mineralization (Fyles and Hewlett, 1959; Legun, 2000). Some of the deposits are described below. Their description is based on our field investigations (2007, 2008) and descriptions of Fyles and Hewlett (1959), Fyles (1964, 1970), Höy (1982) and Legun (2000).

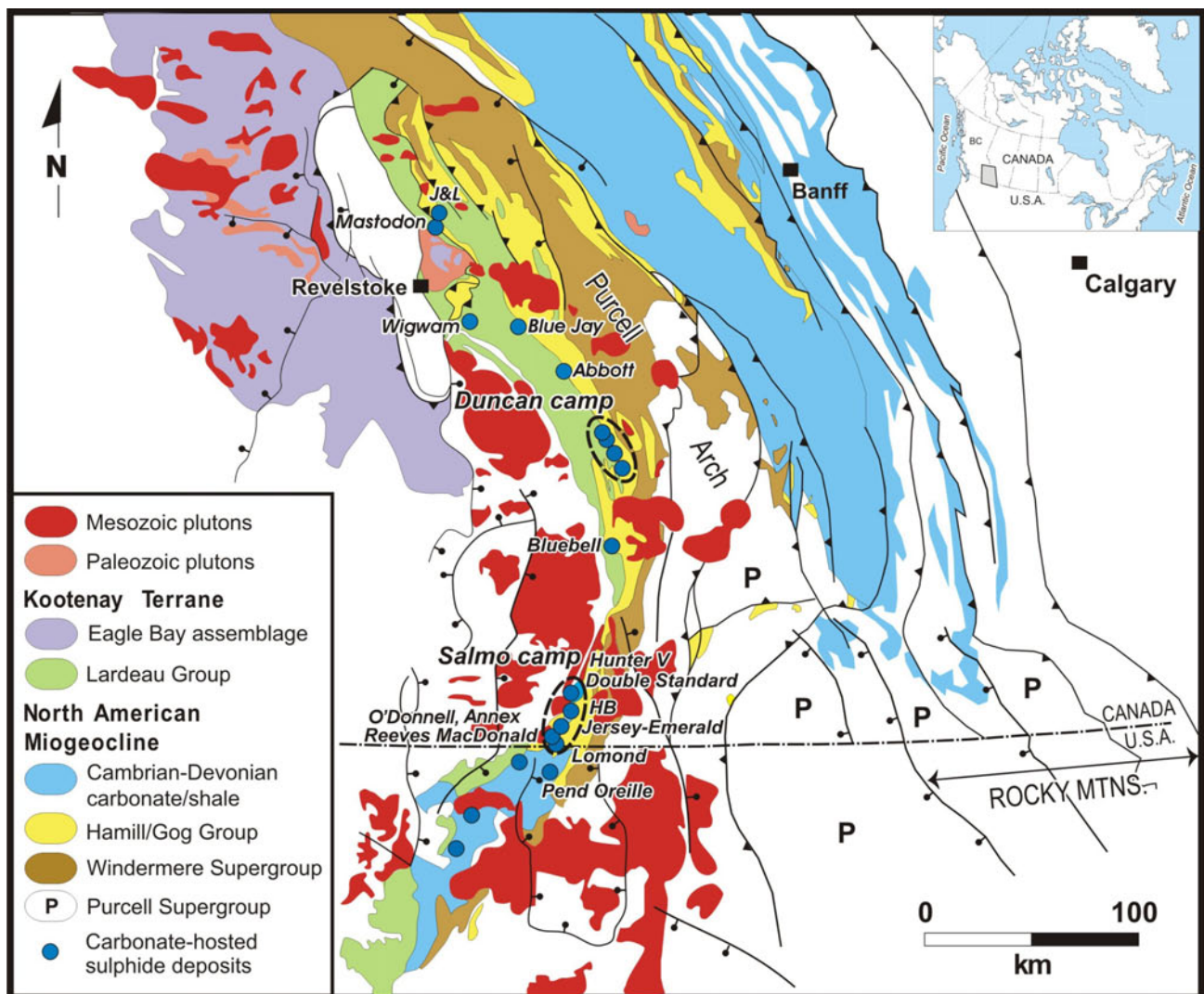


Figure 4. Simplified geological map of southeastern British Columbia showing the Kootenay Arc and location of carbonate-hosted Zn-Pb deposits (modified from Wheeler and McFeely, 1991; Logan and Colpron, 2006; Paradis, 2007).

## CARBONATE-HOSTED NONSULPHIDE DEPOSITS

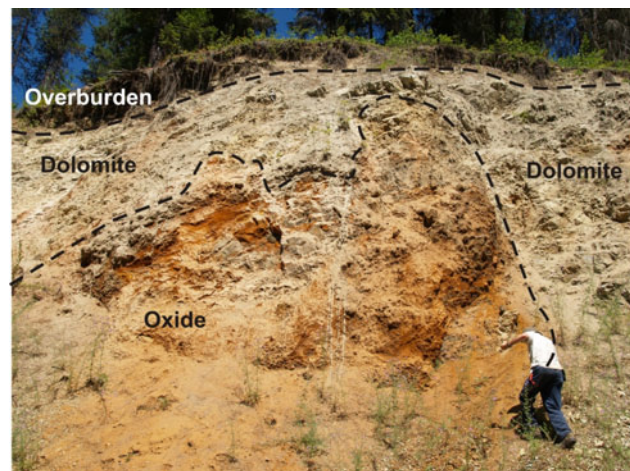
The near-surface portions of the several previously described carbonate-hosted sulphide deposits are weathered, strongly oxidized and consist, in many cases, of extensive Zn- and Pb-bearing, iron oxide gossans and base-metal-bearing nonsulphide minerals. The weathered zones are partially delimited and were not exploited in the past. The mineralogy and paragenesis of oxidized zones are poorly known but indicative of direct-replacement of sulphides by nonsulphide base-metal-bearing minerals. The main exposure at Lomond is an excellent example of a CHNSBM Fe-rich gossan (Figures 1a, 1b, 5). The Oxide deposit may correspond to the hemimorphite portion of a CHNSBM deposit formed by wallrock-replacement (Figure 1b). There are not enough data available to determine conclusively if the Oxide deposit is of the direct- or wallrock-replacement-type but the dominance of hemimorphite is probably linked to high silica activity (provided by the underlying Reno Formation quartzite) during base metal trapping. In most other occurrences, spatial continuity and/or the close spatial relationships in combination with morphological similarities between sulphide and associated nonsulphide zones suggest direct-replacement CHNSBM mineralization. The evidence for direct-replacement origin is strongest where the transition of nonsulphide to sulphide mineralization with increasing depth is well documented. Detailed descriptions of selected deposits are given below.

### **Lomond Deposit (MINFILE 082FSW018)<sup>4</sup>**

This group of occurrences is located approximately 56 km south of Nelson, BC. Highly oxidized Pb-Zn sulphides are exposed within the middle and upper part of the Middle Cambrian to Early Ordovician Nelway Formation, which consists of cream and grey banded dolomite with discontinuous lenses of darker dolomite and dolomitic siltstone (Fyles and Hewlett, 1959). The main showing (Figure 5) is predominantly goethite. It was mined between 1947 and 1948 and in the 1950s as a source of iron for cement making and a small quantity of hand-sorted galena was shipped to the smelter at Trail, BC. Collapsed remnants of ore bins and rails are visible in Lomond Creek upstream from the main showing.

Two oxidized zones, 1.5 and 3.6 m thick and 3 m apart, are described by Fyles and Hewlett (1959) as conformable to the dolomitic banding but locally discordant. They consist of earthy brown, iron oxide limonite(?) containing harder areas of goethite. Within the soft earthy limonite are occasional anglesite-coated nodules of galena. Transparent to translucent crystals of cerussite (0.5–2 mm long) are locally present. A sample of the main oxidized zone assayed 10.3 g/t Ag, 1.2% Pb and 2.7% Zn (Fyles and Hewlett, 1959). The zone was resampled in 2008 and results of the chemical analyses are pending. Associated showings approximately 450 m to the north appear to be covered by debris slides. They were described as podiform, oxidized sulphide zones a few metres across, spaced along a strike length of 300 m. The Lomond showings may be oxidized analogs of the Yellowhead-type mineralization of the Pend Oreille mine in northeast Washington.

<sup>4</sup>(MINFILE, 2008)



**Figure 5.** The main exposure at the Lomond deposit, southeastern British Columbia; an example of a carbonate-hosted, nonsulphide, base-metal (CHNSBM) deposit (gossan component).

### **Reeves MacDonald (MINFILE 082FSW026), Annex (MINFILE 082FSW219), Red Bird (MINFILE 082FSW024) and Related Deposits**

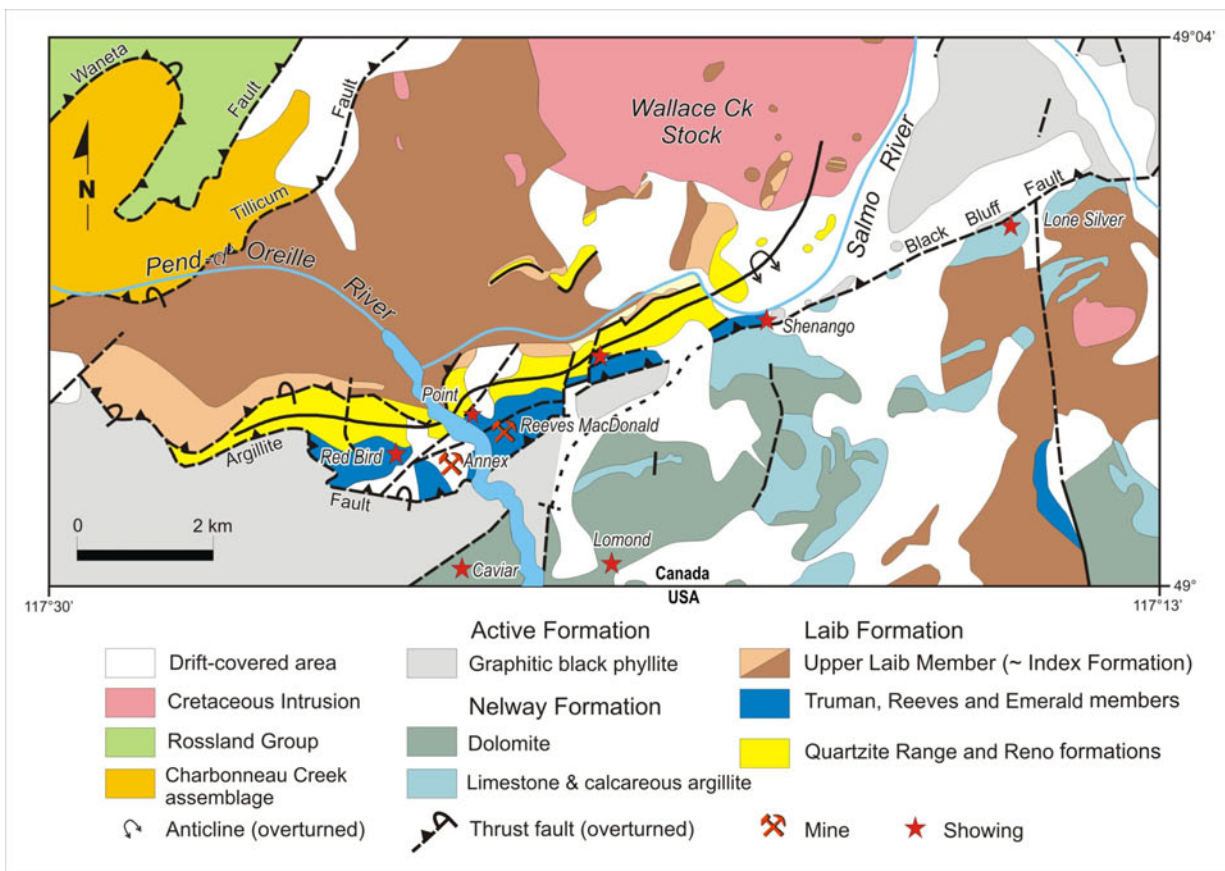
The Reeves MacDonald deposits are located 56 km south-southwest of the village of Salmo. They include the past-producing deposits of Reeves MacDonald and Annex, and the Red Bird prospect.

Combined production from 1949 to 1971 totalled 5 848 021 t of sulphide ore grading 3.50% Zn and 1.39% Pb. From this ore, 19.9 t of Ag, 203 616 t of Zn, 57 693 t of Pb, 1215 t of Cd and 27.6 t of Cu were recovered (MINFILE 082FSW024, 082FSW026, 082FSW219). Like most carbonate-hosted Zn-Pb deposits in the southern Kootenay Arc, the mineralized zones are enclosed by a dolomitized envelope within the Reeves Member limestone. The sulphide orebodies, their enveloping dolomite and the limestone hostrock are folded and metamorphosed to greenschist facies.

Structure in the area is characterized by nearly east-striking foliation and southwesterly trending fold axes. A series of north-striking faults that dip 25–45° east offset the formations and the mineralized zones (Figure 6).

The Reeves, B.L. (MINFILE 082FSW026) and O'Donnell (MINFILE 082FSW028) deposits are interpreted as faulted segments of the same orebody (Fyles and Hewlett, 1959; Gorzynski, 2001). The Red Bird (MINFILE 082FSW024), Annex (MINFILE 082FSW219), MacDonald (MINFILE 082FSW026), Point (MINFILE 082FSW027) and Prospect (MINFILE 082FSW029) deposits may be related by the style of faulting to the above mineralized zones; they may, however, be separate deposits (Fyles and Hewlett, 1959; G. Klein, pers comm, 2007).

The sulphide bodies are structurally conformable and stratabound. The sulphides form bands, lenses and layers of massive to disseminated material parallel to compositional layering within medium to dark grey dolostone. Layering varies from millimetre-scale to several centimetres in thickness, and is continuous over tens of metres, or discontinuous and highly contorted. Lenses of nonmineralized light grey dolomite interlayered with thin bands of argillite



**Figure 6.** Simplified geological map of the Salmo area, southeastern British Columbia (modified from Fyles and Hewlett, 1959).

are common within the ore zones. Sulphides also form a matrix to breccias, which consist of rounded to platy fragments of dolomite, limestone and quartz. The sulphides consist of fine- to medium-grained pyrite, honey-coloured to brown sphalerite, minor galena and traces of chalcopyrite. Copper and cadmium content is typically less than 0.5% and 1 g/t, respectively. Gallium and germanium have been reported in concentrations above background levels.

Only sulphide mineralization was mined and the nonsulphide base-metal-bearing zones, consisting of earthy yellow-brown gossan of limonite(?) and goethite with variable amounts of cerussite, anglesite, smithsonite and hemimorphite, were left behind. According to Höy et al. (1993), the oxidation occurred prior to glaciation and much of the oxidized material was removed by the advancing ice.

Locations and projections of the main mineralized zones to the surface are sketched on Figure 7. The deposits and prospects (Figure 8) are exposed over a distance of approximately 4 km. Some of these mineralized zones, consisting at least in part of nonsulphide base-metal-bearing minerals, are described below.

### MACDONALD ADIT

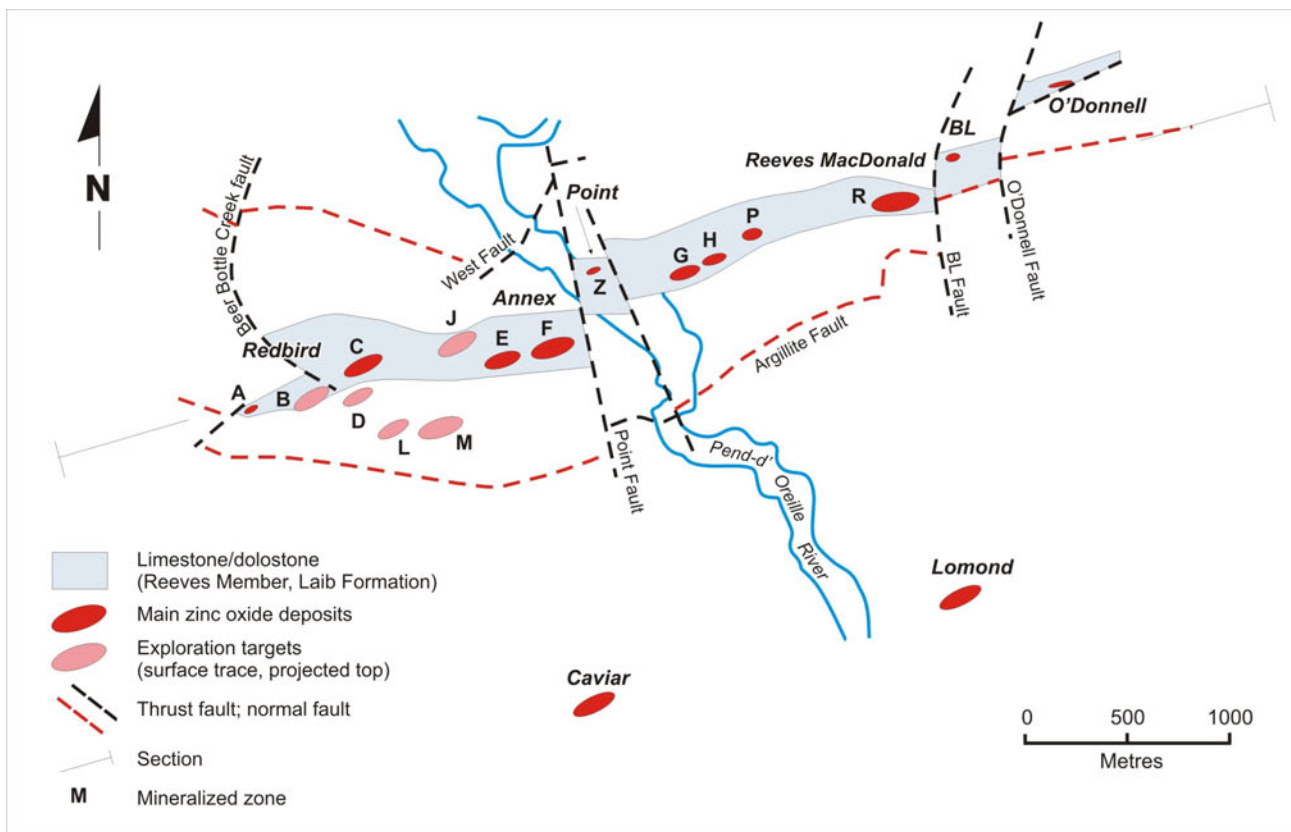
The portal of the MacDonald adit collapsed before 1954 and is now entirely covered by overburden. Fyles and Hewlett (1959) reported that the adit was driven within “earthy calcareous and limonitic materials containing secondary Pb and Zn minerals”.

### POINT (ZONE Z)

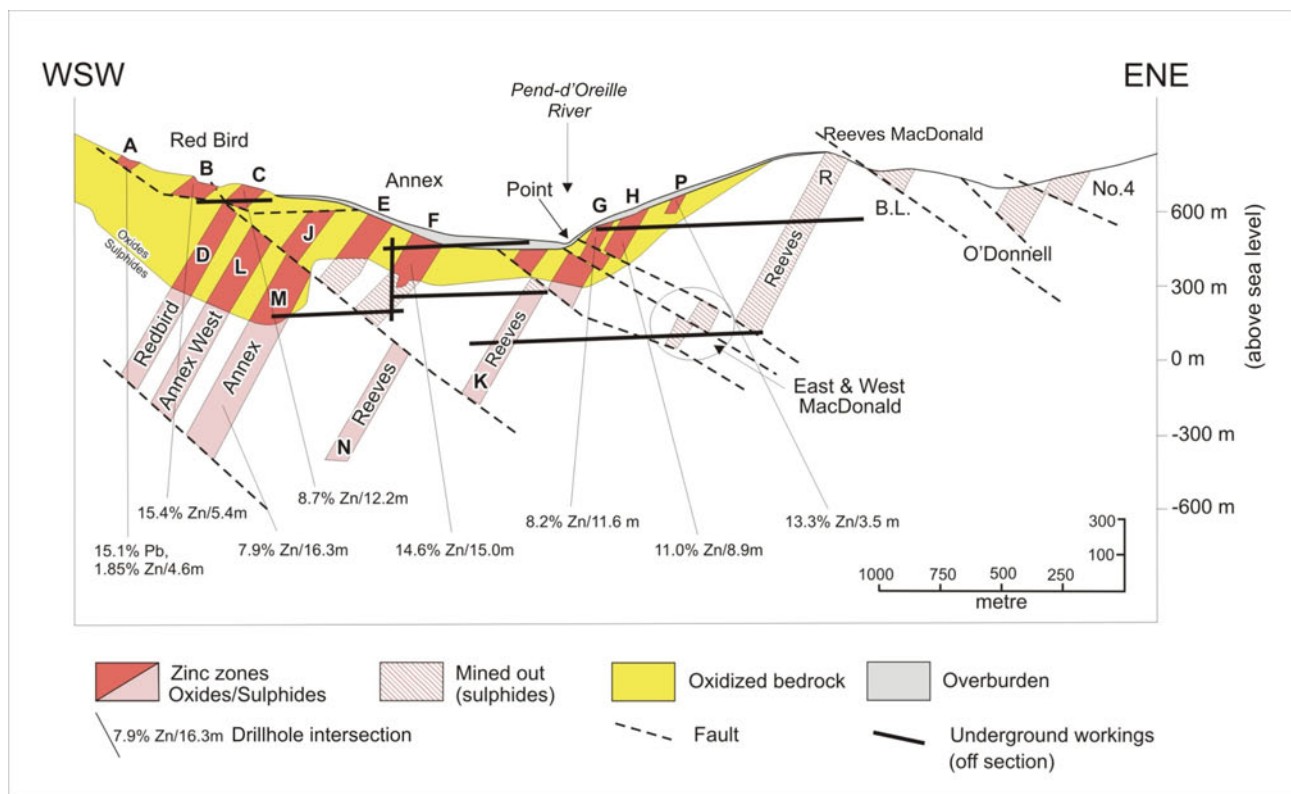
The Point occurrence (zone Z) is located 450 m west of the 1900 level portal of the Reeves MacDonal mine (Figure 8), and most of it is covered by waters of the Pend d'Oreille River. A small faulted section of irregular, tabular masses of limonitic gossan is visible on a roadcut beside the Reeves MacDonal mine road (Figure 9). The Zn-Pb mineralization occurs within irregular, tabular- or pod-shaped envelopes of dolomitized Reeves Member limestone (Fyles and Hewlett, 1959). The deposit consists of two sulphide horizons, each about 6 m thick and separated by 20 m of dolostone. Mineralization consists of bands and lenses of massive and disseminated pyrite, honey-coloured sphalerite and galena. Disseminated, fine-grained, yellow sphalerite and occasional grains of galena also occur in a matrix of brecciated dolomite. A small tonnage of ore, grading 10% zinc was apparently extracted from this zone in the past (Gorzynski, 2001).

### PROSPECT ZONE

The Prospect zone is located in a widespread dolomitized unit informally called the “Prospect dolomite member”. The Prospect dolomite is thought to be a separate carbonate unit from the Reeves Member limestone (G. Klein, pers comm, 2007). It is host to scattered occurrences of disseminated and layered pyrite, sphalerite and traces of galena parallel to a faint layering in the fine-grained, pale grey dolomite. The highest concentrations of sulphides are associated with coarse-grained grey dolomite. The Prospect zone has been tested by two short adits, which exposed irregular and sparse mineralization containing locally 10%



**Figure 7.** Schematic plan view of the main nonsulphide zinc oxide zones within the Reeves Member limestone/dolostone unit of the Laib Formation and the Nelway Formation, southeastern British Columbia (*modified from Redhawk Resources Inc., 2005*).



**Figure 8.** Schematic longitudinal east-northeast section (looking north) showing the distinct nonsulphide zinc oxide and sulphide zones. Some of the nonsulphide zones were labelled A to H by ReMac Zinc Corporation (*modified from Addie, 1970; Price, 1987; Gorzynski, 2001*). For location of section see Figure 7.



Pb and 9% Zn over widths of 60 cm (Walker, 1934). Surface trenching has exposed oxidized zones greater than 4 m across (Fyles and Hewlett, 1959).

Redhawk Resources Inc. drilled four holes in the Prospect dolomite member (south of zone C), which intersected 13.7% Zn over 9 m, 8.24% Zn over 4 m and 2.02% Zn over 16.98 m (Klein, 1999).

## ANNEX MINE

The Annex mine (consisting mainly of zones E and F), located on the west side of the Pend-d'Oreille River (Figure 7), operated from 1970 to 1975. It produced 763 314 t of sulphide ore at a recovered grade of 5.59% Zn, 0.93% Pb and 44.61 g/t Ag, most of which came from the E and F zones (Figure 8). Several boreholes drilled from 1986 to 2000 returned significant Zn, Pb and Ag grades within the nonsulphide portions of the Annex mineralization (George Cross News Letter, 1998; Klein, 1998). The last two holes were drilled in 2000 to intersect the upward projection of the sulphide zone. The first hole averaged 9.64% Zn over 21.0 m, with high-grade footwall (18.47% Zn over 3.9 m) and hangingwall (23.75% Zn over 2.3 m) portions and with lower grade dolomitic sections. The second hole averaged 14.62% Zn over 15.0 m without internal dolostone sections. These are the only holes in the area that encountered nonsulphide mineralization below the water table (Gorzynski, 2001). The position of the sulphide-oxide boundary in zone F is known and was established during mining. At both of these holes, drilling also encountered long sections of low-grade mineralization below the main intersections (21.4 m section of dolostone grading 1–2.4% Zn and a 23.4 m section grading 1–5% Zn).

## ZONE G

Zone G is another faulted section of the Annex mine. The first 500 m from the portal of the Reeves 1900 level is in leached limestone with iron oxide zones that were formed by oxidation of the MacDonald sulphide orebody (Fyles and Hewlett, 1959). This oxide zone was further investigated by drilling in 2000 (Gorzynski, 2001). The best intersection was 8.21% Zn, 1.08% Pb and 6.5 g/t Ag over 11.6 m (Gorzynski, 2001). This confirms the presence of base-metal nonsulphide mineralization above the zones encountered in the 1900 level.

## ZONE H

Zone H hosts zinc oxide mineralization. It is interpreted to continue at depth where grab samples of zinc oxides grading 20–25% Zn were collected from underground workings in the early 1970s (G. Klein, pers comm, 2000; Gorzynski, 2001). One of the two holes drilled in 2000 returned 10.98% Zn over 8.9 m, including 14.71% Zn over 5.3 m of true width. A second drillhole located 55 m to the east, returned 6.35% Zn over 4.4 m of true width but the intersection was near surface (Gorzynski, 2001).

## ZONE P

Zone P is a zinc oxide zone discovered by drilling in 2000. A drillhole returned two mineralized intersections, 6.68% Zn over 4.4 m (near the surface) and 13.25% Zn over 3.5 m at depth (Gorzynski, 2001).



**Figure 9.** Limonitic gossan is visible on a roadcut beside the Reeves MacDonald mine road, the Point occurrence (zone Z), southeastern British Columbia.

## Red Bird Prospect

The Red Bird prospect lies south and west of the Pend-d'Oreille River along Red Bird Creek. It includes zones A, B, C and D described below (Figures 7, 8). The main workings include four adits, a shaft and several more recent trenches and roadcuts. All the underground workings are inaccessible. The indicated resource (which predates National Instrument [NI] 43-101) within the Red Bird prospect is reported at 2 177 040 t grading 18.5% Zn, 6.5% Pb and 68.5 g/t Ag (Price, 1987).

## ZONE A

Zone A is located near the old Red Bird no. 4 tunnel. The trenches exposed narrow zones of zinc oxide mineralization in dolostone of the Reeves Member. Gorzynski (2001) reported values of 5.4% Zn over 1.6 m, 6.42% Zn over 1.3 m and 16.11% Zn over 1.5 m.

## BEER BOTTLE ZONE (ZONE B)

The Beer Bottle zone, located approximately 300 m east of zone A (Figures 7, 8), has been traced over a strike length of 110 m. It is truncated to the east by the Beer Bottle Creek fault and remains open to the west (Klein, 1999; Gorzynski, 2001).

The zone has been known since the 1920s and was drilled and retrenched in 1998 and 2000. One of the trenches exposed a section of red-brown limonite intercalated with dolostone (Gorzynski, 2001) and returned 15.00% Zn over 12.8 m. The footwall portion of this zone assayed 22.16% Zn over 6.3 m and the hangingwall portion returned 8.08% Zn over 6.5 m (Gorzynski, 2001). Four other trenches returned disappointing results but one of the roadcuts exposed a 10 m long section interpreted as a collapse breccia (Gorzynski, 2001). According to Gorzynski (2001), the breccia consists of angular dolostone and limestone and rounded clasts of zinc oxide (mainly hemimorphite) varying in size from pebbles to boulders. Five hemimorphite-rich boulders sampled on the property contained 18–32% Zn. Four vertical channel samples taken over the 10 m breccia exposure averaged 17.76% Zn (Gorzynski, 2001).

Based on the above description, this nonsulphide zinc oxide section is very different from other typical nonsulphide mineralization of the Salmo area. Other nonsulphide, karst-related, Zn occurrences are known elsewhere (Hitzman et al., 2003).

### **ZONE C**

Zone C, located 150 m northeast of zone B, is one of the main mineralized zones of the Red Bird prospect exposed at surface. It is interpreted as a down-faulted portion of zone B (Figure 8). Red Bird tunnel no. 1 exposed a nonsulphide section of approximately 140 m in length, including a 75 m long and over 6 m wide zone that has an average grade of 18.55% Zn, 5.97% Pb and 36.7 g/t Ag (Emendorf, 1927; Sorensen, 1942; Gorzynski, 2001). One of the re-excavated roadcuts (60 m in length), located 85 m in elevation above tunnel no. 1, exposed a limonite section that returned 6.93% Zn over 21 m (Gorzynski, 2001). High-grade zones in the footwall and hangingwall of this section assayed 12.30% Zn over 4.4 m and 9.75% Zn over 5.6 m. This zone includes two lenses of low-grade dolostone and a lower grade, iron oxide-rich, central section (3.32% Zn over 11.0 m), which is interpreted as direct-replacement of the pyrite-rich protore.

### **ZONE D**

Zone D was found by deep drilling. One drillhole reported an oxidized intersection of 16.7 m that assayed 7.2% Pb, 8.95% Zn and 23.5 g/t Ag, directly overlying a 1.5 m sulphide-rich dolomite section that assayed 5.64% Zn, 0.38% Pb, 8.8 g/t Ag and 0.06% Cd (Price, 1987). Consequently, the position of this zone (Figure 8) is based entirely on interpretation.

### ***Caviar Showing (MINFILE 082FSW060)***

The Caviar showing consists of two zones located west of the Pend-d'Oreille River and 200 m north of the United States border (Figure 7). These zones consist of lenses and stringers of sphalerite in dolomitic sections of limestone of the Nelway Formation (Fyles and Hewlett, 1959; Gorzynski, 2001). The best of four drillholes returned an intersection of 6.5% Zn over 6 m (Crosby, 1956). The nonsulphide (near surface) portion of the mineralization is believed to be limited to a few metres.

### ***Jersey-Emerald Deposits (MINFILE 082FSW009)***

The Jersey-Emerald property lies approximately 11 km southeast of the village of Salmo. It encompasses the former Jersey and Emerald Zn-Pb mines, and the Emerald, Feeney, Invincible and Dodger tungsten mines. Other deposit types, such as a gold-bismuth zone, SEDEX-type zinc-silver-copper deposits and molybdenum porphyry deposits are also present on this property. Only the Zn-Pb deposits will be considered here.

The historic Jersey Zn-Pb deposit was a small but steady producer from 1906 to 1925. During that period 25 850 t of ore were mined and 705 292 g of Ag, 6 788 936 kg of Pb and 19 771 kg of Zn were recovered. During 1948, when the Emerald tungsten mine was in production, a large tonnage of lead-zinc ore was outlined by drilling at the Jersey Zn-Pb mine. The Jersey Zn-Pb mine operated continuously until 1973. Lead and zinc was pro-

duced from Jersey and Emerald orebodies. Between 1949 and 1973, over 8 million tonnes of ore grading 1.95% Pb and 3.83% Zn were mined and 115 000 t of Pb, 263 000 t of Zn and 21 500 kg of Ag were recovered (MINFILE 082FSW009; Sultan Minerals Inc., 2008).

The Jersey and Emerald Zn-Pb mineralization occurs within a dolomitized zone, near the base of the Reeves Member and varies from 8 to 30 m in thickness. The Truman Member of the Laib Formation forms the mine footwall rocks (Fyles and Hewlett, 1959). It consists of dense, reddish green skarns and a brown argillite hosting tungsten and molybdenum mineralization. Five Pb-Zn dolomite-hosted ore bands, ranging in thickness from 0.3 to 9 m, are recognized within the mine. Sulphide ore consists of fine-grained sphalerite and galena with pyrite, pyrrhotite and minor arsenopyrite. The galena-sphalerite-pyrite-pyrrhotite ores are banded and similar to ores from the HB deposits, except that Pb dominates. Cadmium is associated with low-iron sphalerite and silver with galena. In 1995, during a tungsten exploration program, diamond drilling encountered a second Pb-Zn-bearing dolomite horizon located 55–60 m below the Jersey mine, currently referred to as the Lower Jersey zone (Sultan Minerals Inc., 2008). The widest mineralized intercept was 9 m, and the best single intersection graded 8.1% Zn and 3.8% Pb across 1 m (George Cross News Letter, 1997).

Unlike many of the other carbonate-hosted Pb-Zn deposits in the Salmo area, there is no record of a near-surface oxidation zone. Generally, this agrees with our field observations. The mine is dry and only two of the ten ore zones, B and D, were exposed at surface. Both of these zones are elongated approximately northward and plunge gently south. Only the southern-most and topographically lowest portions of these orebodies outcropped on Iron Mountain. A Fe-rich gossan was noted and sampled at 1394 m of elevation, west of the Emerald Zn-Pb mine portal no. 1. Results of geochemical analyses of this oxide zone are pending.

### ***HB Deposit (MINFILE 082FSW004)***

The HB mine is located 8 km southeast of the village of Salmo. It consists of two distinct zones, the HB and the Garnet deposits. The HB deposit consists of at least five orebodies and the Garnet deposit is a single lens. The mine produced a total of 6 656 101 t of ore between 1912 and 1978. Measured and indicated reserves, published in 1978 (predating NI 43-101) by Canadian Pacific Limited, were 36 287 t grading 0.1% Pb and 4.1% Zn (Anonymous, 1983).

The orebodies, hosted by Reeves Member limestone, are located less than 100 m west of the Argillite fault. Sedimentary rocks in the mine area are folded into a broad synclinorium, and the limestone-dolostone beds hosting the orebodies are on the west limb of this structure. Isoclinal folding is described within the trough of the synclinorium and these folds are affected by crossfolding at the north end of the HB mine and south of the main orebody.

The HB main mineralization consists of three elongated, crudely ellipsoidal orebodies dipping steeply toward the east and plunging 15–20° southward. These steeply dipping orebodies are connected by two gently dipping tabular sulphide breccia bodies, which also plunge 15–20° southward (MINFILE 082FSW004). The steeply dipping orebodies consist of concentrations of discontinuous stringers that have a Pb:Zn ratio of 1:5, whereas the tabular

brecciated mineralized zones have a Pb:Zn ratio of approximately 1:2.5 (MINFILE 082FSW004). The sulphide concentrations within steeply dipping ore zones appear to be parallel to cleavage in the host dolomitic marble (MacDonald, 1973). Sulphide mineralization within the tabular zones appears to follow the bedding.

Sulphide minerals consist predominantly of fine-grained pyrite and subordinate sphalerite, galena and locally minor pyrrhotite. The sulphide mineralization is enveloped by a broad zone of dolomitization, which is bordered along its contact with limestone by a narrow silica-rich zone. Talc and tremolite are reported to be found mainly near the silica-rich zone, suggesting that these minerals formed along the front produced by synmetamorphic element exchange between silica-rich and dolomitic rocks. Alternatively, tremolite and talc may be part of a metasomatic front created by the introduction of silica-bearing fluids into the dolomitic carbonates.

The northern portions of the mineralized zones are exposed at surface and oxidized to a depth of 100 m (Fyles and Hewlett, 1959). Available evidence points to the origin by the direct-replacement process. Nonsulphide minerals include hemimorphite  $\{Zn_4Si_2O_7(OH)_2 \cdot H_2O\}$ , smithsonite  $\{ZnCO_3\}$ , cerussite  $\{PbCO_3\}$  and anglesite  $\{PbSO_4\}$ . Fyles and Hewlett (1959) also mentioned the following phosphates: pyromorphite  $\{Pb_5(PO_4)_3Cl\}$ , hopeite  $\{Zn_4(PO_4)_2(OH)_2 \cdot 3H_2O\}$ , spencerite {an uncommon zinc phosphate;  $Zn_4(PO_4)_2 \cdot 4H_2O$ } and salmoite  $\{Zn_2(PO_4)(OH)\}$ .

### Oxide Prospect (MINFILE 082FSW022)

The main showings of the Oxide prospect outcrop to the west of the north-striking Oxide pass, 5.5 km east-southeast of Ymir, BC. The area is underlain by black argillite and slate of the Lower(?) to Middle Ordovician Active Formation, grey limestone of the Reeves Member of the Laib Formation, and micaceous and white quartzite resembling the lower Nevada Member of the Quartzite Range Formation (Fyles and Hewlett, 1959).

The fault zone (up to 9 m wide) consists of crushed and sheared rocks, containing a muddy clay-like gouge about 0.5 m thick (Fyles and Hewlett, 1959; MINFILE 082FSW022). The nonsulphide base-metal-bearing zone at



**Figure 10.** Hemimorphite-bearing material, Oxide deposit, south-eastern British Columbia.

the Oxide adit was reported to be highly oxidized and was exposed along strike for 458 m with a maximum width approaching 9 m. Past drilling and underground development confirmed that the oxidized zone extends more than 180 m in depth. Figure 10 shows the typical exposure in the vicinity of the Oxide fault. The limonitic gossan contains hemimorphite (Figure 11) and parahopeite as the major Zn-bearing minerals (McAllister, 1951). Galena nodules and pyromorphite are the principal Pb-bearing minerals (McAllister, 1951). The highest assay from the adit in 1948 was 15.7% Zn, 1.4% Pb, 0.34 g/t Au and 3.4 g/t Ag (Fyles and Hewlett, 1959). Up to 23% manganese and minor pyritic quartz, with low gold assays, are reported in MINFILE (082FSW022). The International adit, located approximately 830 m to the south of the Oxide adit, intersects an oxide zone up to 7.3 m in width, which is also reported to host nonsulphide Zn-Pb mineralization.

## DISCUSSION

The Reeves MacDonald group of deposits represent the best documented examples of CHNSBM deposits in BC. Figure 8 summarizes relationships between the base-metal, nonsulphide mineralization and the sulphide ore within the Reeves MacDonald area. Sulphide zones were oxidized at least up to 450 m below the surface. Several CHNSBM zones are underlain by sulphide mineralization, suggesting that they formed by direct-replacement of sulphide deposits. This is also supported by their mineralogy and Pb and Zn content.

The key controls on the formation of CHNSBM deposits are climate, nature and availability of near-surface protore, lithology, favourable hydrology and the rate of uplift.

Climate and paleoclimate are important factors in the selection of any given area for exploration targeting supergene CHNSBM deposits (Hitzman et al., 2003; Reichert and Borg, 2008). The climate controls the oxidation conditions and the transport of metals. The most favourable conditions for oxidation are achieved in an arid climate, which maximizes the quantity of metals available for transport by supergene solutions. This is done by minimizing biogenic activity within the soil, making more oxygen available for sulphide oxidation and maximizing the



**Figure 11.** Cut through a hemimorphite nodule from Oxide deposit, south-eastern British Columbia, displaying characteristic texture.

quantity of metals that are available for transport by solutions (Reichert and Borg, 2008). Dry climate also favours a low water table, preventing premature dilution of metal-bearing supergene solutions by barren ground water within aquifers and dispersion of the ore-forming metals (Reichert and Borg, 2008). There is no detailed information regarding the paleoclimate in the Salmo area but studies from southern BC indicate that after the last glacial maximum (from 17 000 to 14 000 BP) there was a relatively warm and dry climate around 10 000–7 000 BP (Palmer et al. 2002; Hebda, 2007). This warm dry period may have been ideal for development of CHNSBM deposits.

Areas not affected by glaciation have higher potential to contain preserved, soft, CHNSBM deposits than glaciated ones. The Late Wisconsinan Cordilleran Ice Sheet originated in the Canadian Cordillera and its progression southward was to a large extent controlled by topography (Clague and James, 2002). The last ice sheet started to develop 30 000–25 000 BP and reached its maximum extent 17 000–14 000 BP. Its retreat was accompanied by brief readvances, down wasting and periods of stagnation. According to Clague (1991, Figure 12.1), the Salmo area is located about 100 km north of the maximum southern limit of this ice sheet. The glaciers in the Salmo area may have been thin. Isostatic rebound, which started during the glacial retreat, was probably less in the Salmo area than in areas originally covered by thicker ice.

Sulphide mineralization in the Salmo area is premetamorphic and predeformational (pre-Middle Jurassic). From the field evidence, we know that the sulphide oxidation is post-Middle Jurassic, and may have started before or slightly after the last glacial maximum (17 000–14 000 BP). The relatively warm and dry climate, which prevailed some 10 000–7 000 BP (Palmer et al. 2002; Hebda, 2007), may have been particularly favourable for supergene oxidation of sulphides and formation of CHNSBM deposits in the Salmo area. If this scenario is correct, the formation of CHNSBM deposits coincided with glacial retreat, which also favoured their preservation.

## EXPLORATION CONSIDERATIONS

The selection of grassroots exploration areas involves considering the conditions required or favouring the formation of CHNSBM deposits, such as the presence of known sulphide mineralization containing base-metal-bearing sulphide deposits, favourable climate and/or paleoclimate (which influences the position of the water table and the prevailing oxido-reduction conditions), permissive hydrological characteristics (permeability and porosity of the hostrocks, karsts, and fracture and fault zones), availability of rocks with ability to control the pH of the metal-bearing solutions (carbonates), topography, rate of uplift and glacial history.

Common nonsulphide ore minerals are Zn, Pb and Fe oxides, carbonates, silicates and phosphates (Table 1). With the exception of the Fe-bearing minerals that are common in gossans (Fe-oxyhydroxites, goethite and hematite), these minerals are unfamiliar to today's field geologists. Training in mineralogy, use of a colorimetric field test for zinc ("Zinc Zap"), use of portable X-ray fluorescence (XRF) analyzers and use of heavy mineral surveys (most of the nonsulphide base-metal ore minerals have high densities [Table 1]) will improve the odds for new discovery. Some of the nonsulphide base-metal-bearing minerals may

fluoresce under ultraviolet light (Table 1). Hydrozincite and smithsonite generate distinct short-wave, infrared-spectral responses, therefore under favourable conditions the use of short-wave infrared spectrometry (SWIR) and remote sensing may be justified. Monitoring the water table during an exploration drilling program is essential and obtaining records from water well logs in neighbouring areas may provide useful information. Electronically available results of Regional Geochemical Surveys (available on the MapPlace website; BC Geological Survey, 2008) are useful. Glaciation reduces the chances of preserving the soft CHNSBM deposits. Tracing mineralized glacial erratics back to their source may help to locate such deposits. From a geophysical point of view, nonoxidized sulphide zones containing pyrrhotite will have the best potential to be detected by airborne electromagnetic (EM) surveys. The self-potential (SP) method is ideal to detect zones of active sulphide oxidation, unfortunately the method has a very limited depth of penetration.

Regardless of the intensity of the glacial scouring and erosion, the shape and orientation of the CHNSBM bodies appears to be key to their preservation through the glaciation. Steeply plunging, rod-shaped nonsulphide oxide deposits (such as those of the Reeves MacDonald area), with their smallest dimension exposed at surfaces (Figure 8), enclosed in competent rocks (i.e., dolomitized limestone), have excellent preservation potential. Flat-lying exposed deposits, with the largest dimensions coplanar with erosion surface have lowest survival potential. On the positive side, local, small-scale transportation of nonsulphide ore fragments from steeply plunging CHNSBM bodies is considered beneficial for exploration.

## CONCLUSION

The association of many known CHNSBM zones with underlying massive sulphides in combination with nonsulphide ore characteristics suggests that a large proportion of known CHNSBM mineralized zones in the Salmo area are of the direct-replacement type. Geologists and prospectors look instinctively for red gossan, which is commonly associated with near-surface oxidation of sulphides; however, high-grade Zn, white ores are more difficult to recognize. At least in some cases, massive, nonsulphide white ores were not visually distinguished in the past from the common barren dolostone (Gorzynski, 2001). While the locations of a large proportion of outcropping red ore nonsulphide deposits in the Salmo area are probably already known, it is conceivable that economically significant Zn-rich CHNSBM deposits containing white ore remain to be discovered. There are many genetic factors, such as the timing of the oxidation of sulphides that remain to be better constrained. The Salmo mining camp can be considered an example of economically significant near-surface CHNSBM deposits within a glaciated area. Shape and orientation of a CHNSBM deposit may be the key factor that determines if a given deposit survives glaciation or not.

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