Carbonate Alteration Footprints of Carbonate-Hosted Zinc-Lead Deposits in Southeastern British Columbia (NTS 082F/03): Applying Carbon and Oxygen Isotopes

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Introduction

The hydrothermally altered hostrocks that result from the formation of many mineral deposit systems, such as porphyry, volcanogenic massive sulphide (VMS), epithermal and orogenic gold, can form large concentric haloes of visibly altered rocks that define the alteration footprints of that specific ore deposit type. By contrast, deposits that form in carbonate hostrocks typically have narrower and less-intensely developed alteration footprints, and so these hydrothermal systems generate significantly smaller visible and geochemical haloes. However, carbonate-hosted deposits can have cryptic or invisible alteration footprints that are much broader when detected with analyses of light stable isotopes. It has been shown that stable isotope alteration can be detected at distances of up to 3 km laterally around the mineralization core. As such, stable isotope alteration haloes are typically larger than the limits of the orebody, visible alteration or even geochemical anomalies (Barker et al., 2013).

Light stable isotopes of common elements in ore systems, such as carbon, oxygen, hydrogen and sulphur, have been utilized to understand fluid-rock interactions in and around ore deposits for more than 40 years (Nesbitt, 1996). The intensity of this isotopic alteration increases from peripheral regions into the centre of mineralization with greater shifts toward lighter isotopic ratios occurring with more fluid-rock interaction. These lighter stable isotope ratios can therefore provide information about fluid flow during mineralization. This in turn can enable the mapping of the extent of fluid interactions, discern fracture-controlled versus pervasive permeability, determine alteration temperatures, assess alteration intensity, and contribute to the development of ore deposit and exploration models (Barker et al., 2013).

Keywords: carbonate, British Columbia, Zn-Pb deposits, C and O isotopes, isotopic footprint

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This particular project is focused on characterizing the carbonate alteration footprints of the relatively poorly understood Zn-Pb deposits in southeastern British Columbia. These deposits are poorly classified and have been variably attributed to a range of mineral deposit models, such as sedimentary exhalative, Irish-type, carbonate replacement-type and skarns (Fyles, 1970; Simandl and Paradis, 2009), and further complications arise because many deposits also include oxidized Zn ores (Simandl and Paradis, 2009).

This paper aims to outline the Masters project initiated at the Mineral Deposit Research Unit (MDRU) at the University of British Columbia. This project is included in the MDRU's Carbonate Alteration Footprints Project. The main project objectives are as follows:

- determine the size and intensity of alteration surrounding different types of carbonate-hosted Zn-Pb deposits within southeastern BC,
- characterize and map fluid flow pathways and assess the intensity of fluid-rock interactions as vectoring tools,
- assess stable isotope alteration from proximal intrusion-related through to distal carbonate-hosted ore systems, and
- determine the optimal sampling protocols and strategies to utilize stable isotopes as an exploration tool.

Regional Geology

Geology

Southeastern BC is underlain by the central part of the Kootenay Arc, a curving belt of complexly deformed sedimentary, volcanic and metamorphic rocks extending from Revelstoke southeast, south and southwest across into northeastern Washington (Fyles, 1967). These rocks represent the ancient western margin of the ancestral North American miogeocline. The rock units of the central Kootenay Arc comprise Lower Cambrian micaceous quartzite of the Reno Formation overlain by the Cambrian Laib Formation, containing the Truman, Reeves and Emerald members (Figure 1). The Truman member of the lower Laib Formation consists of a thin sequence of interbedded

Period	Southeastern British Columbia		
Ordovician	Active Formation		
Middle Cambrian	Nelway Formation		
Lower Cambrian	Laib Formation	upper Laib Formation	
		Emerald member	
		Reeves member	
		Truman member	
	Reno Formation		
	Quartzite Range Formation		

Figure 1. Schematic stratigraphic log of the regional geology in southeastern British Columbia (modified from Fyles, 1970).

phyllite and limestone. The Reeves member mainly consists of fine- to medium-grained limestone, which has been locally altered to dolostone. This limestone characteristically displays grey, black and white banding typically a few centimetres in width. The dolostone often weathers buff, is poorly banded or massive, and is normally finer grained than the limestone. The Emerald member overlies the Reeves member limestone and is characterized by a black to grey, foliated, carbonaceous, often crenulated, phyllite unit. At the top of the Laib Formation (the upper Laib Formation) is an undivided series of phyllite units with lesser intercalated beds of micaceous quartzite and limestone (Fyles and Hewitt, 1959).

The Laib Formation is overlain by the Middle Cambrian Nelway Formation (Figure 1), a second unit of limestone and dolomite. Above the Nelway Formation is the Ordovician Active Formation (Figure 1); a unit of black argillite slate with minor calcareous lenses (Fyles and Hewitt, 1959). Throughout southeastern BC there are numerous intrusions of Mesozoic granite, leucocratic granite and syenite. These have traditionally been considered part of the Nelson batholith suite, which has been dated as Middle Jurassic (Little, 1960).

Structure and Metamorphic History

The rocks of the Kootenay Arc have a complex structural history involving at least three phases of folding, major regional low-angle faults and multiple smaller faults (Fyles and Hewitt, 1959). Notably, the regional trend is to the northeast, which is contrary to the typical northwesterly trend of the Cordillera.

Regional metamorphism reaches to lower greenschist facies and is thought to have been synchronous with the earliest phase of deformation. Contact metamorphism is locally associated with the intrusion of the Middle Jurassic igneous rocks and postdates all phases of folding (Fyles and Hewitt, 1959).

Mineralization

Carbonate-hosted Zn-Pb deposits occur along the entire length of the Kootenay Arc with the largest deposits occurring in the vicinity of Salmo, BC and Metaline Falls, Washington, on either side of the Canada–United States border. From north to south, the major carbonate-hosted Zn-Pb deposits of the Kootenay Arc include the Duncan, H.B., Jersey, Remac and Pend Oreille deposits (Figure 2). These deposits can be split into two end-members (Fyles, 1970):

- Salmo-type deposits consist of stratiform lenses of pyrite, sphalerite and galena in zones of dolomite in the highly deformed Lower Cambrian Reeves member limestone. These types of deposits include the Duncan (near the north end of Kootenay Lake), the H.B., Jersey and Remac orebodies.
- Metaline-type deposits consist of stratiform lenses in the relatively undeformed, stratigraphically younger, Middle Cambrian Nelway Formation carbonate rocks. These types of deposits include those situated near Metaline Falls, Washington, in particular, the Pend Oreille deposit.

Deposit Geology

The three deposits that this project is focused on are Remac, Jersey and H.B. (Figure 2). The property geology for each of these deposits is discussed further below.

Remac

The Remac property is located east of the junction of the Salmo and Pend-d'Oreille rivers, approximately 56 km south-southwest of Nelson and 25 km southeast of Trail (Figure 2). Between 1949 and 1971, whilst the mine was active, 5.8 million tonnes of ore was recovered at 3.5% Zn, 1.39% Pb, 0.02% Cd and 3.12 g/t Ag (MINFILE 082FSW026, BC Geological Survey, 2014). Three regional-scale packages of rocks are present at the property: the Reeves member, the Active Formation and the Nelway Formation. These rock units typically strike west-southwest and dip steeply to moderately to the south (Fyles and
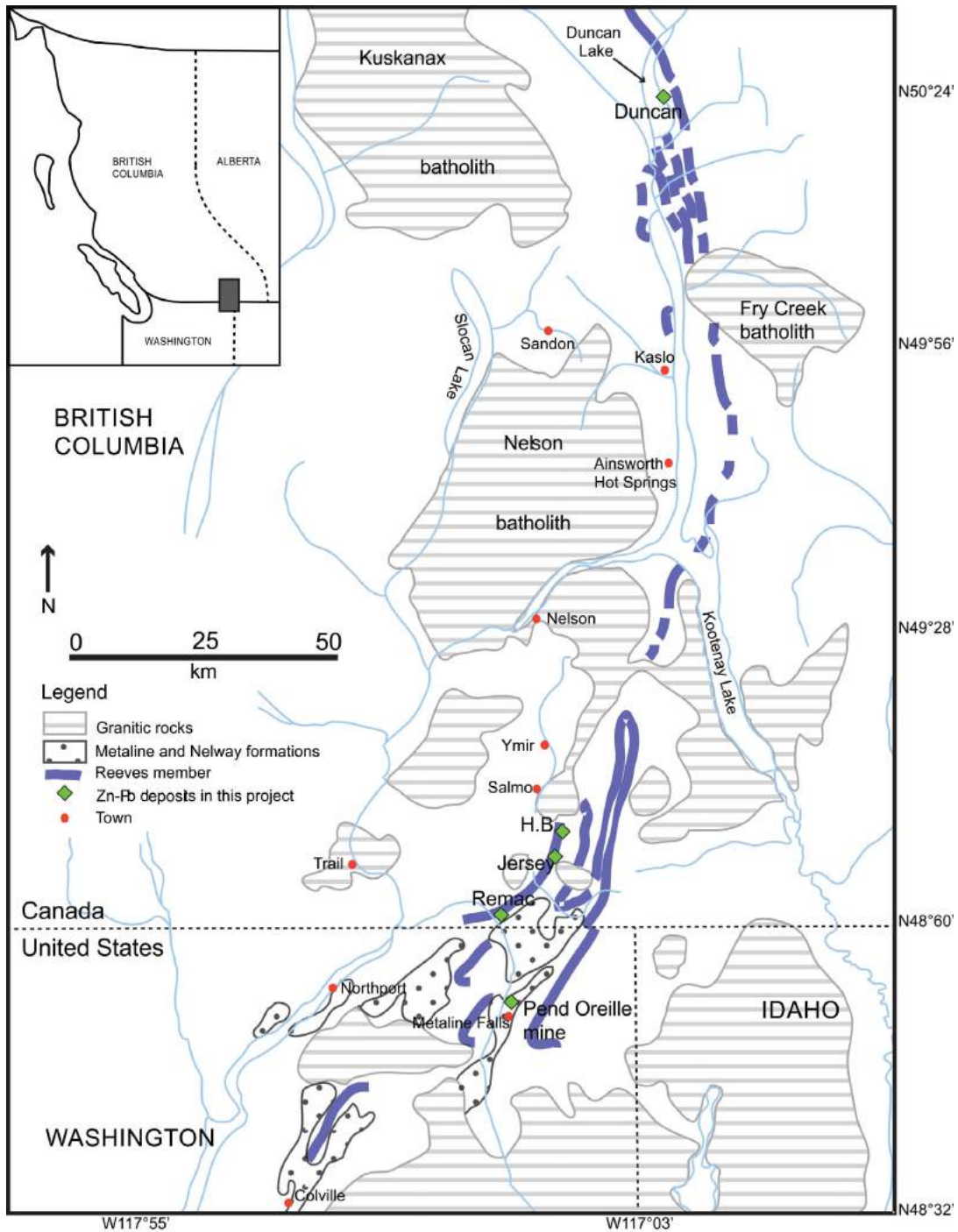
Figure 2. Location map of the three properties studied in this project and their corresponding bedrock geology, southeastern British Columbia (modified from Fyles, 1970).

Hewitt, 1959). All significant Zn-Pb mineralization within the Remac property occurs in the Reeves member carbonate rocks, which can be split into three property-scale subunits (Kushner, 2009).

The northern Reeves horizon is an extensive unit of massive to bedded limestone that appears to be devoid of base metal mineralization. The central Reeves horizon is host to all the past Zn-Pb production from the mine and the majority of other known Zn-Pb mineralization on the property. The southern Reeves horizon is host to scattered zones of Zn-Pb mineralization (Kushner, 2009).

The Reeves member limestone is medium grained, weathers blue-grey and is thinly banded between white, grey and sometimes black intervals. These laminations are generally
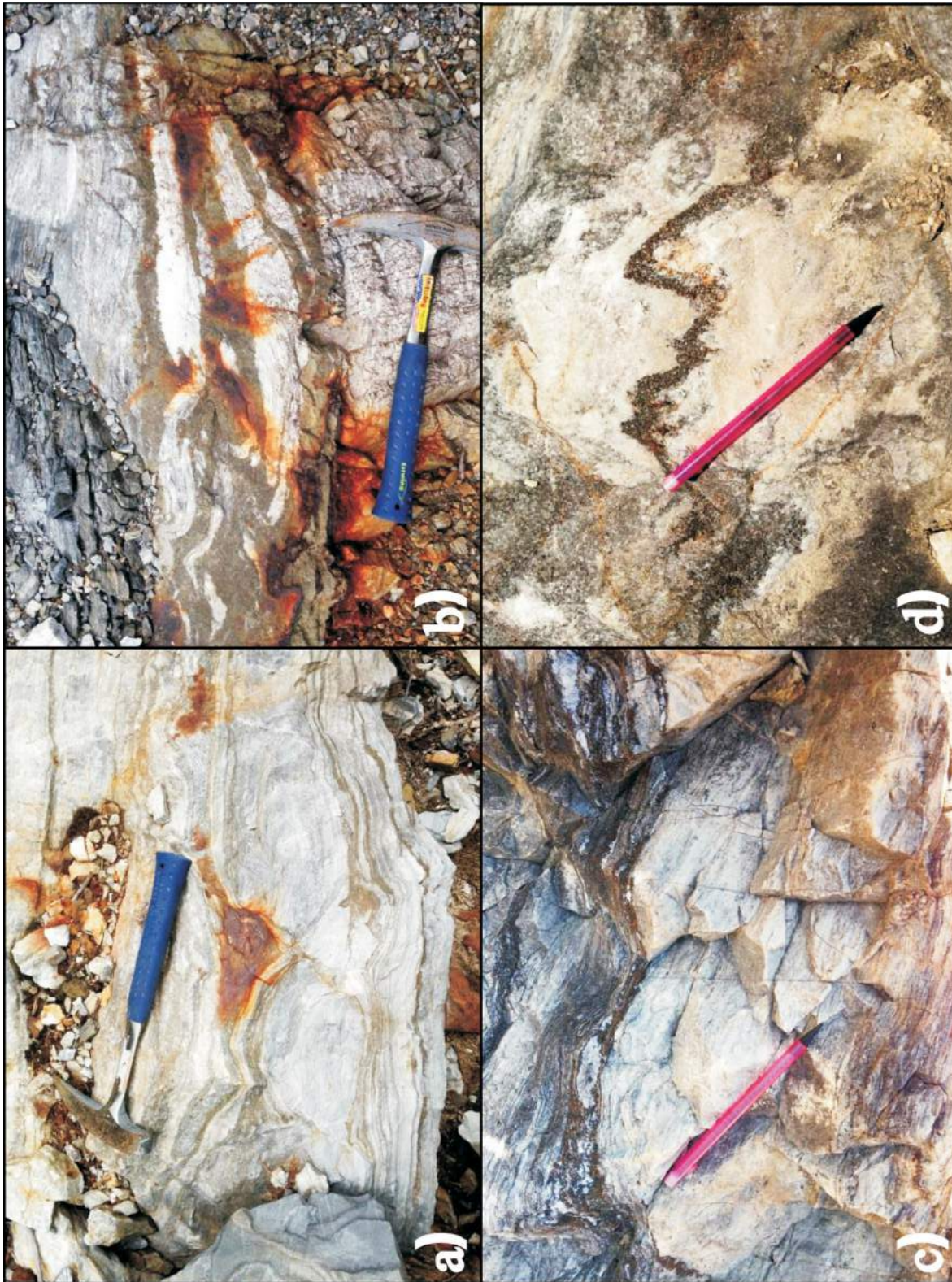
Figure 3. Collage of photographs to show the mineralization styles seen at the Remac (a, b) and Jersey (c, d) deposits, southeastern British Columbia. **a)** Deformed lenses of sulphides within the Reeves member at the Remac deposit. **b)** Deformed lenses of pyrite within the Reeves member at the Remac deposit; mineralization wraps around a dolomite boudin. **c)** Stratiform lenses of pyrite, sphalerite and galena within the Reeves member dolomite at the Jersey deposit. **d)** Deformed band of pyrite within the Reeves member limestone at the Jersey deposit.

on the scale of one to several centimetres. Primary sulphide mineralization at the Remac property consists of laminations and lenses of massive and disseminated pyrite, honey-coloured sphalerite, galena and trace chalcopyrite within the Reeves member. The sulphide bodies are structurally conformable and stratabound, and often contain a high-grade central core that typically feathers out along strike. The sulphide bodies are typically contained within dolomite envelopes, some of which extend for considerable distances along strike (Figure 3a, b). The dolomites tend to be finer grained and more massive than the nearby limestone (Kushner, 2009).

Conformably overlying the ore-bearing limestone of the Reeves member are black, carbonaceous phyllite and schist of the Emerald member of the Laib Formation. The characteristic rock type that comprises the Emerald member is a black to grey, foliated, often crenulated, phyllite unit. Disconformably overlying the Laib Formation is the Ordovician Active Formation. The Active Formation consists of black argillite slate and minor calcareous members (Fyles and Hewitt, 1959).

Rocks present on the Remac property are deformed by two major west-southwest-trending, isoclinal folds: the Salmo River anticline and the Reeves syncline. These folds have moderate to steep southerly dipping axial planes. The rocks are also cut by a series of north-northeasterly trending normal faults. These faults dip 45 to 60° to the east, and have resulted in a downfaulted repetition of the stratigraphic and mineralized sequence eastward in a number of separate fault blocks (Fyles and Hewitt, 1959).

Jersey

The Jersey property sits at the summit between Sheep and Lost creeks, roughly 11 km southeast of Salmo (Figure 2). Between 1949 and 1970, whilst the mine was active, 6.4 million tonnes of ore was recovered at 4.1% Zn and 1.2% Pb. Measured and indicated ore reserves as of April 1, 1965, are reported at 671 075 tonnes grading 4.1% Zn and 1.2% Pb (MINFILE 082FSW009). The property is underlain by rocks of the Truman member, composed of interbedded thin grey and white, locally dolomitic limestone. The Emerald member is a black argillite unit. The Reeves member consists of limestone and dolomite and the upper Laib Formation is composed of green phyllite and micaceous quartzite. These sedimentary rocks are intruded by small plugs, dikes and sills of Cretaceous granite and those that are in contact with the granitic bodies are typically skarnified, resulting in a variety of skarn rocks ranging from recrystallized coarse-grained marble to garnet-pyroxene–bearing skarn (Giroux and Grunenberg, 2010).

The Zn-Pb deposits on the Jersey property are hosted by fine-grained, poorly layered to massive dolomite of the Reeves member (Simandl and Paradis, 2009). This miner-alization (Figure 3c, d) occurs near to the base of the Reeves member and forms stratiform lenses of pyrite, sphalerite and galena in dolomitized zones (Simandl and Paradis, 2009). The dolomites are texturally distinct from the medium-grained, well banded, grey and white limestone unit of the Reeves member. The deposits, their dolomitic envelopes and the limestone hostrock generally lie within secondary isoclinal folds along the limbs of regional anticlinal structures (Giroux and Grunenberg, 2010). Five ore bands, ranging in thickness from 0.3 to 9.0 m have been identified. These bands in order of stratigraphic sequence are
1) upper lead band,
2) upper zinc band,
3) middle zinc band,
4) lower zinc band, and
5) lower lead band.

The Truman member of the Laib Formation forms the mine footwall rocks. It consists of dense, reddish green skarns and a brown argillite that hosts W and Mo mineralization (Giroux and Grunenberg, 2010).

Several zones of significant and locally very different mineralization have been identified. Historically, mined areas produced Zn, Pb and W, with known areas of high Mo, Au, Bi, As, Cu, Ag, Cd and Ba concentrations (Giroux and Grunenberg, 2010).

The rocks present on the Jersey property have been deformed by three phases of folding. Within the mine area, structure is dominated by a major north-northeast-trending anticline, which is also present at the Remac property, known as the Salmo River anticline. The property mineralization is associated with the east limb of this anticline (Giroux and Grunenberg, 2010). Three small stocklike bodies of Cretaceous granite intrude the Salmo River anticline and locally cut the ore zones near the Jersey mine. From south to north these are the Jersey, Emerald and Dodger stocks (Giroux and Grunenberg, 2010).

H.B.

The H.B. property is located on Aspen Creek, a tributary of Sheep Creek, 8 km southeast of Salmo (Figure 2). Between 1912 and 1978, whilst the mine was active, 6.7 million tonnes of ore was recovered at 4.1% Zn and 0.1% Pb. Measured and indicated reserves as of December 31, 1978, are reported at 36 287 tonnes grading 4.1% Zn and 0.1% Pb (MINFILE 082FSW004). The property is underlain by the Reeves member limestone and the Lower to Middle Ordovician Active Formation. These units contact each other along a fault, with the Active Formation rocks overthrust from the east over the Reeves member rocks (Giroux and Grunenberg, 2010). Two distinct calcareous layers of the Reeves member can be recognized in the area, an upper unit about 110 m thick separated from a lower 12 m member by 15 to 30 m of micaceous, brown, limey argillite. The H.B.

orebodies occur roughly 100 m to the west of the thrust fault. It is thought that the mineralization is related to the intrusion of granitic stocks of the Middle to Late Jurassic Nelson intrusion. However, the only intrusions present in the mine are post-ore diabase dikes up to 3 m thick (Giroux and Grunenberg, 2010).

The mineralized zones are located within dolomitized limestone of the Reeves member and contain banded galena, sphalerite, pyrite and pyrrhotite similar to that seen at the Jersey property except that Pb dominates (Giroux and Grunenberg, 2010).

In the vicinity of the H.B. mine, the beds are folded into a broad synclinorium, and the limestone layers in the mine are on the west limb of this structure. The principal ore zones consist of three, steeply dipping, parallel zones lying approximately side by side and extending as pencil-like shoots for about 900 m along the south plunge of the controlling structures (Giroux and Grunenberg, 2010).

Light Stable Isotopes

Studies of light stable isotopes (S, C, O and H) have attempted to characterize isotopic footprints of a variety of carbonate-hosted ore systems, but have yet to be extensively used in BC's Zn-Pb deposits. It has been shown that light stable isotope studies, when used in conjunction with geological data, fluid inclusion studies and geochemical data, can not only identify fluid components, but also place important constraints on their evolution in the system, for example, origin of the ore fluid (Rye, 1993). The use of stable isotopes in these systems is enabled by the fact that their host ore fluids undergo considerable fluid-rock interaction.

Stable isotope analyses are traditionally measured using gas-source isotope ratio mass spectrometry (IRMS). However, C and O isotope ratios can now be analyzed using infrared absorption to measure isotopic signatures in different gas species. One such infrared absorption technique, which has been developed and applied at MDRU, is off-axis–integrated cavity output spectroscopy (OA-ICOS). The OA-ICOS uses a laser source, which produces light at an infrared wavelength suitable for interacting with the gas species of interest (Barker et al., 2013).

The stable isotope composition of hostrocks that have interacted with hydrothermal fluid will depend on a variety of factors:
- the isotopic composition of unaltered hostrock,
- the isotopic composition of the hydrothermal fluid, and
- the temperature of dissolution and precipitation.

In general, rocks that have seen higher degrees of fluid-rock interaction, or where fluid-rock interaction occurred at higher temperatures, will have a greater shift toward lighter isotopic ratios. Therefore, hostrocks in the vicinity of mineralization should be expected to have the lightest isotopic values compared to rocks farther from mineralization. Furthermore, the size and distribution of isotopic alteration is likely controlled by the total flux of hydrothermal fluid and, as such, is controlled by permeability, mineralogy, grain size, temperature and fluid-rock ratios in the surrounding hostrocks (Barker et al., 2013).

Conclusion

This project aims to improve the current understanding of southeastern BC's poorly understood Zn-Pb deposits by applying stable isotope studies to map out their alteration footprints. Stable isotopes have been used to successfully understand fluid-rock interactions in and around a variety of ore deposits for more than 40 years (Nesbitt, 1996). It stands to reason that the same techniques can be applied to less well understood deposit types in order to aid in the mapping of the extent of fluid interactions, discern fracture-controlled versus pervasive flow, determine fluid temperatures, assess alteration intensity, and contribute to the development of ore deposit and exploration models. It is hoped that this technique will improve the current deposit model for Zn-Pb systems in southeastern BC and could potentially be used as an exploration tool to find similar, undiscovered deposits in the area. This, in turn, may revive southeastern BC as a region of potential economic development and so generate more interest in the nearby communities of Salmo, Nelson and Trail.

To date, fieldwork has been conducted on the Remac, Jersey and H.B. deposits to collect a variety of carbonate samples for C and O isotope analysis. Roughly 500 samples were collected in September 2014 with particular focus being put on sampling: unaltered, unmineralized, carbonate hostrocks distal to the main ore zones; all observable dolomite phases; mineralized samples proximal to the main ore zones; and any late-stage carbonate veins. Furthermore, representative samples of all main rock types have been collected for thin-section petrography. Preliminary C and O isotope analysis will be conducted on these samples in the coming months in addition to petrography, carbonate staining, ultraviolet-light analysis and scanning electron microscope–cathodoluminescence (SEM-CL) analysis. It is anticipated that all of these techniques will characterize the carbonate alteration footprint of these poorly understood Zn-Pb deposits and provide a paragenetic sequence of events for each deposit, which in turn may be used to improve the current deposit models in this area. This Masters project is anticipated to be completed in January 2016.

Acknowledgments

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