Uranium-Lead Age Constraints and Structural Analysis for the Ruddock Creek Zinc-Lead Deposit: Insight into the Tectonic Evolution of the Neoproterozoic Metalliferous Windermere Supergroup, Northern Monashee Mountains, Southern British Columbia (NTS 082M)

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Introduction

The Ruddock Creek property (Figure 1) is situated within the Windermere Supergroup of the northern Monashee Mountains of British Columbia. Structurally, the Ruddock Creek property is interpreted to reside within the base of the Selkirk allochthon, in the immediate hanging wall of the Monashee décollement, a crustal-scale, thrust-sense ductile shear zone. Crustal thickening associated with polyphase deformation involved at least three episodes of superposed folding of rocks in the region and two prograde metamorphic events (Fyles, 1970; Scammell and Brown, 1990; Scammell, 1993; Höy, 2001). At Ruddock Creek, Fyles (1970) identified three phases of ductile deformation. The first phase of folding is interpreted to coincide with development of Early to Middle Jurassic southwest-vergent fold nappes that dominate the macroscopic structure of the southern Omineca Belt (Brown et al., 1986; Brown and Lane, 1988; Scammell, 1993; Figure 2a). At the property and outcrop scale, this first phase of folding is manifest as rootless isoclinal recumbent folds (Figure 2a). The second and third phase of folding are interpreted to have developed during Early Cretaceous northeast-vergent deformation (Scammell, 1993). Second phase folds (F_2) are tight to isoclinal overturned toward the northeast (Figure 2b) and are refolded by coaxial third phase folds that are more open and upright (Figure 2c). The final phase of deformation is related to late brittle faulting (Figure 2d).

The lithological units that occur throughout the area include: quartzite, pelitic and semipelitic schist, quartz-feldspar psammite, calcsilicate gneiss and marble. Nepheline-syenite gneiss and syenite gneiss occur as concordant layers within the calcsilicate gneiss. Pegmatite and granitoid intrusions account for approximately 50% of the overall outcrop (Fyles, 1970; Scammell, 1993; Höy, 2001). The metasedimentary rocks are thought to belong to the Windermere Supergroup (Scammell, 1993), which is an important stratigraphic succession in the North American Cordillera interpreted to have been originally deposited along the rifted western margin of Laurentia during Neoproterozoic time (Gabrielse, 1972; Stewart, 1972, 1976; Burchfield and Davis, 1975; Stewart and Suczek, 1977; Monger and Price, 1979; Eisbacher, 1981; Scammell and Brown, 1990; Ross, 1991). However, the age of the rocks that host the Ruddock Creek deposit and their stratigraphic position within the Windermere Supergroup are not well constrained. Estimates based mainly on lithological correlations within the Kootenay terrane and North American rocks to the east range from Mesoproterozoic to Paleozoic (Scammell, 1993).

During the Neoproterozoic, the horst and graben topography along the rifted western Laurentian margin controlled the sedimentary facies of the Windermere Supergroup and the potential formation of sedimentary exhalative (SEDEX) deposits (Goodfellow and Lydon, 2007; Lund, 2008). For instance, reactivation of faults along the irregular horst and graben topography may have provided a conduit system for the auriferous hydrothermal fluids driven by deeper seated magmatism, which is syngenetic with sedimentation (McMechan, 2012). The Ruddock Creek deposit is thought to represent one of these rift-related SEDEX deposits hosted within the Windermere Supergroup (Höy, 2001; Simpson and Miller-Tait, 2012).

Throughout the Canadian Cordillera, the temporal and spatial distribution of rift-related SEDEX deposits defines major metallogenic periods (MacIntyre, 1991). A major metallogenic event is associated with continued Early to Middle

Keywords: *U-Pb geochronology, Windermere Supergroup, SEDEX deposit, Cordilleran tectonics*

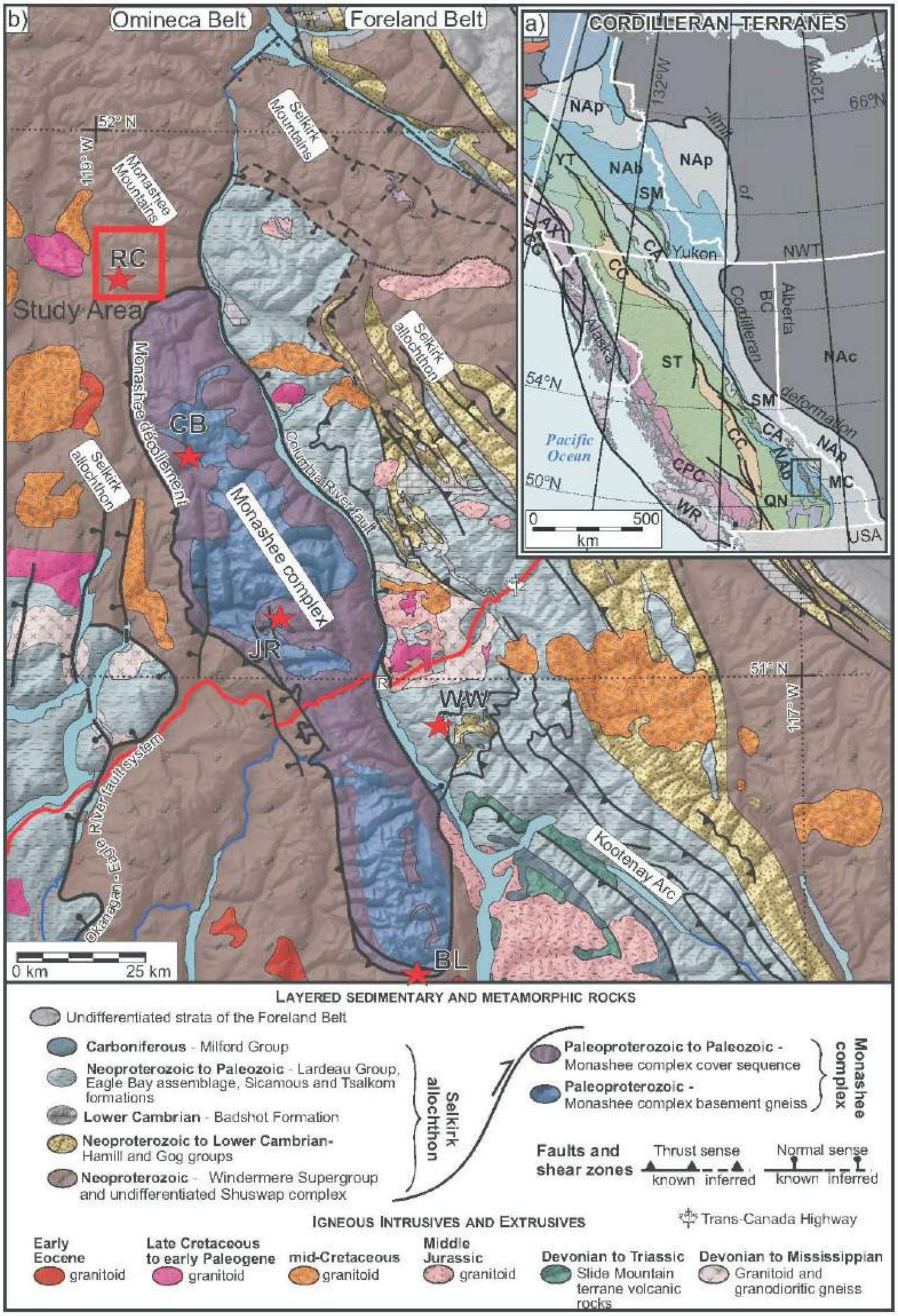

Figure 1. Regional geology of the southern Omineca Belt. **a)** Cordilleran terrane map (after Colpron and Nelson, 2011). Terranes: AX, Alexander; CA, Cassiar; CC, Cache Creek; CG, Chugach; CPC, Coast plutonic complex; MC, Monashee complex; NAb, North American basinal; NAc, North American craton and cover; NAp, North American platform; QN, Quesnellia; SM, Slide Mountain; ST, Stikinia; YT, Yukon-Tanana; WR, Wrangellia. Location of tectonic assemblage map indicated by the black box. **b)** Tectonic assemblage map, southeastern Omineca Belt, southern British Columbia (after Wheeler and McFeely, 1991; Gibson et al., 2008), showing lithological units of autochthonous Monashee complex (North American basement) and overlying Selkirk allochthon. Location of study area indicated by the red box. Red stars indicate location of major Pb-Zn deposits in the region: BL, Big Ledge; CB, Cottonbelt; JR, Jordan River; RC, Ruddock Creek (this study; see Figure 2); WW, Wigwam. Town: R, Revelstoke.

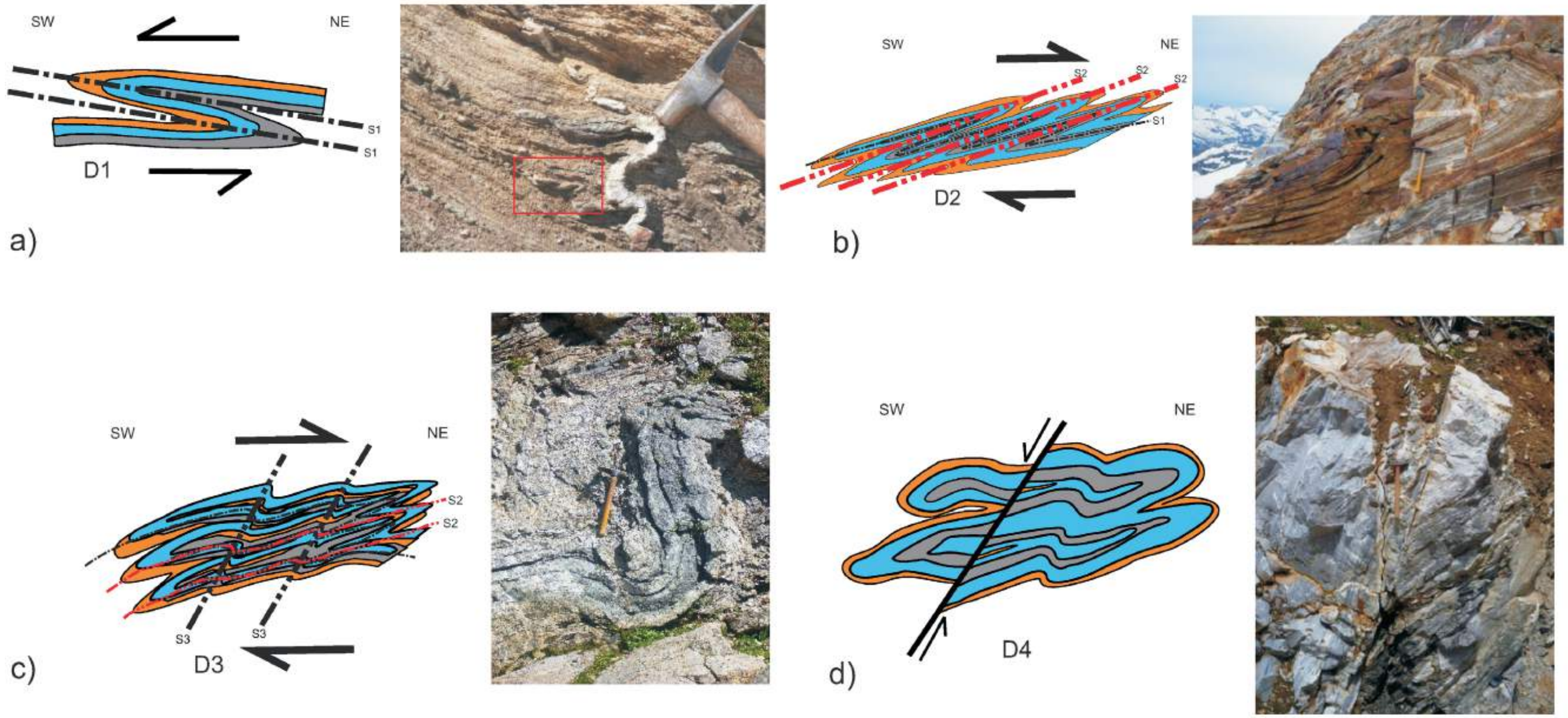

Figure 2. Schematic representation of deformation events that have affected the Ruddock Creek deposit, southern British Columbia. **a)** First phase of deformation (D_1), include southwest-vergent kilometre-scale nappe folds (F_1). The photo shows relict F_1 folds observed at outcrop scale preserved as rootless folds in the penetrative S_2 foliation. **b)** Second phase of deformation (D_2), characterized by overturned northeast-vergent isoclinal folds (also shown in photo) that are axial planar to the S_2 transposition foliation. **c)** The third phase of deformation (D_3) refolds F_2 folds and S_2 foliation into more open, northeast-vergent folds as seen in the photo. **d)** The fourth phase of deformation (D_4) consists of late brittle faults with minor observable offset (metres to tens of metres) and fault block rotation as shown in the photo.

Cambrian rifting of the margin that resulted in a series of uplifted and topographically higher sections that were capped by platformal sedimentary rocks. In the southern Canadian Cordillera, the Kootenay terrane and Monashee complex host shallow-water carbonate rocks and interbedded clastic rocks that underlie the strataform Pb-Zn deposits of the Kootenay Arc, and Shuswap and Adams plateaus (MacIntyre, 1991; Nelson, 1991).

The focus of this project is placed on 1) constraining the age of the Ruddock Creek deposit and evaluating the genetic relationship between several mineralized zones that comprise the deposit using detrital zircon U-Pb dating and Pb isotopic analysis, 2) refining the structural history through mapping at 1:10 000 scale, and 3) relating the deposit to the metallogenic evolution of the Canadian Cordillera.

Regional Geology

The southern Omineca Belt (Figure 1) is the penetratively deformed metamorphic and plutonic hinterland to the Foreland (thrust-and-fold) Belt of the Canadian Cordillera, and is the result of long-lived convergence, primarily Mesozoic, between the North American craton and oceanic lithosphere, which resulted in collision between accreted terranes ferried in on the subducting oceanic crust and the westward underthrusting of the North American plate (Monger et al., 1982; Brown et al., 1992; Monger and Price, 2002; Gibson et al., 2008). The southern Omineca Belt includes North American basement and overlying strata and marks the transition between the ancient continental margin and accreted juvenile intra-oceanic rocks to the west (Monger et al., 1982). The study area lies within the parautochthonous Kootenay terrane of the southern Omineca Belt (Figure 1; Colpron and Price, 1995; Colpron et al., 2007), underlain by mainly clastic and carbonate rocks with lesser mafic volcanic rocks of the Neopro- terozoic Windermere Supergroup (Scammell, 1993). In this region, the Kootenay terrane is situated within the Selkirk allochthon (Brown and Lane, 1988), which represents the hanging wall of the Monashee décollement, a crustal-scale northeast-vergent ductile shear zone (Read and Brown, 1981). The Monashee complex is the footwall of the Monashee décollement (Read and Brown, 1981), and is interpreted as a core complex that includes exposed Laurentian basement (Brown and Read, 1983; Journeay, 1986; Scammell and Brown, 1990; Armstrong et al., 1991; Crowley, 1999) in two tectonic windows, the Frenchman Cap dome and Thor Odin dome (Figure 1). The basement is mostly composed of granitic orthogneiss that ranges from 2270 to 1870 Ma (Armstrong et al., 1991; Crowley, 1997, 1999). The Monashee complex was tectonically exhumed during Eocene (55–45 Ma) extension, following a major orogenic episode of crustal thickening related to Mesozoic to earliest Paleogene (>60 Ma) compression (Monger et al., 1982; Brown et al., 1986; Parrish, 1995; Crowley, 1999; Monger and Price, 2002; Gibson et al., 2008). The Monashee complex is bounded on the east by an early Paleogene (~55 Ma), east-dipping, normal fault referred to as the Columbia River fault (Read and Brown, 1981).

The regional geology of the Monashee Mountains, within which the Ruddock Creek deposit is found, has been divided into three crustal domains (Carr, 1991; Scammell, 1993) that are distinguished by distinct but associated tectonothermal histories. These domains were at different crustal levels within the Cordilleran orogen prior to Eocene extension (Carr and Brown, 1989; Carr, 1992). The domain that represents the deepest crustal level includes the Malton gneiss complex, Monashee complex and core of the Valhalla complex (Simony et al., 1980; Armstrong, 1982; Brown et al., 1986; Carr et al., 1987; Armstrong et al., 1991). The upper boundary is marked by crustal-scale thrust-sense shear zones, which include the Malton décollement, Monashee décollement and the Gwillim Creek shear zones (Simony et al., 1980; Read and Brown, 1981; Brown et al., 1986; Journeay, 1986; Carr et al., 1987).

The mid-crustal domain consists of the penetratively deformed amphibolite-facies rocks in the hanging wall of the aforementioned shear zones, and in the vicinity of the Monashee complex, the hanging wall rocks are part of the Selkirk allochthon within the Kootenay terrane (Read and Brown, 1981; Wheeler and McFeely, 1991; Scammell, 1993). The upper boundary of the mid-crustal domain is marked by east- and west-dipping crustal-scale normal faults (Read and Brown, 1981; Tempelman-Kluit and Parkinson, 1986; Parrish et al., 1988; Johnston and Brown, 1996; Brown et al., 2012). The upper crustal domain lies in the hanging wall of the normal faults and generally consists of lower metamorphic grade, polydeformed Upper Proterozoic to Jurassic sedimentary and mafic igneous rocks, and Eocene volcanic and sedimentary rocks (Carr, 1991).

Previous Work and Geology of the Ruddock Creek Deposit

The earliest exploration and mapping of the Ruddock Creek property was done in the 1960s and 1970s by Cominco Ltd. (The Consolidated Mining and Smelting Company of Canada), Falconbridge Ltd. and Doublestar Resources Ltd. Regional-scale mapping in the 1970s was carried out by Fyles (1970) as part of a preliminary study of Pb-Zn deposits in the Shuswap metamorphic complex for BC's Department of Mines and Petroleum Resources. The purpose of his work was to describe the structure and lithology of the rocks associated with the conformable Pb-Zn deposits, which focused in part on the Ruddock Creek deposit. More recently, the Ruddock Creek property was acquired by Selkirk Metals Corp. in 2005. In 2010, Selkirk Metals Corp was sold to Imperial Metals Corporation and became Ruddock Creek Mining Company. Since those early days, Ruddock has seen over 88 000 m of drilling, the development of an underground decline, support roadways and a substantial camp built onsite. In 2012, Ruddock Creek Mining Company invested in a bulk sample, which was taken from the deposit's main zone (the E zone), and metallurgical analysis of the sample. The current resource estimate at the Ruddock Creek deposit is 10 036 000 tonnes of 8.07% combined Zn and Pb (indicated and inferred resource at 4% cutoff).

Additional regional work was carried out by Scammell (1993) who examined the mid-Cretaceous to Paleogene thermotectonic history of former mid-crustal rocks within the northern Monashee Mountains of the southern Omineca Belt. Scammell's work included regional mapping and structural analysis, U-Pb geochronology, thermochronology and thermobarometry. The U-Pb dating of two-mica leucogranite suggested three periods of magmatism: 135 ±2 Ma, ca. 100 to 97 Ma and ca. 71 to 57 Ma. Scammell also suggested that the penetrative ductile strain in the Selkirk allochthon was heterogeneous and developed between ca. 135 and 97 Ma. In addition, he proposed that 'dynamic spreading' involving horizontal extension during constructive orogeny was accompanied by the removal of approximately 10 km of crust from 100 to 94 Ma.

As mentioned above, the host stratigraphy for the Ruddock Creek deposit is thought to belong to the Windermere Supergroup (Scammell, 1993). Although the Windermere Supergroup is arguably one of the most important stratigraphic successions in the Canadian Cordillera, there is a paucity of modern U-Pb dating of detrital zircon for the Windermere Supergroup in this part of the Canadian Cordillera. Past multigrain and single grain isotope dilution–thermal ionization mass spectrometry (ID-TIMS) dating of detrital zircon was undertaken by Ross and Bowring (1990), Ross and Parrish (1991), Smith and Gehrels (1991), Gehrels and Dickinson (1995) and Gehrels and Ross (1998). These studies returned Archean and Early Proterozoic ages that are the hallmarks of cratonic basement sources with Laurentian provenance, but left open the possibility for significant refinements to be made regarding the actual age of the Windermere Supergroup at any given interval and location. Hence, this was deemed to be one of the foci of the current study. With regard to the timing constraints for the various Zn-Pb deposits in the region, Höy (1987) produced a Cambrian Pb model age for the Cottonbelt deposit, 50 km to the south in the Monashee complex. Curiously, the mineralization occurs only a few hundred metres stratigraphically above the basal part of the Monashee complex cover sequence, which is interpreted to be Paleoproterozoic in age (Crowley, 1997; see also Scammell and Brown, 1990). Millonig et al. (2012) reported a U-Pb zircon age of ca. 360 Ma for the strataform Mount Grace carbonatite horizon, which underlies the Cottonbelt Pb-Zn deposit. The date suggests that the Cottonbelt deposit is either much younger than the Cambrian Pb model age or the Mount Grace carbonatite represents a stratigraphically higher unit that is now found structurally beneath the Cottonbelt deposit due to folding and/or faulting.

Methods

This study integrated a broad range of analytical techniques in the field and laboratory to obtain a robust constraint on the structural control of the mineralization and the maximum depositional age of the Ruddock Creek stratabound Zn-Pb deposit and its host stratigraphy, as well as determine the Pb isotopic signature of the deposit.

Field Mapping

Fieldwork involved property mapping at a 1:10 000 scale and mapping of the mineralized horizons at a 1:5000 scale. Structural data, oriented samples for microstructural analysis, and geochronological and Pb isotope samples were collected. Mapping focused on the structural geometry of the deposit and the geological relationships of the mineralized horizon.

Petrographic Analysis

Oriented hand samples from representative sites across the property have been cut into thin section and are being used for ongoing microstructural and petrographic analysis. Thin sections from all the geochronological and Pb isotope samples were also made in order to characterize the lithologies, contact relationships and mineral assemblages.

U-Pb Geochronology

Zircon U-Pb data were obtained from 12 metasedimentary samples and 2 igneous samples from the Ruddock Creek property and nearby vicinity (see Figure 3 for sample locations). Zircon crystals were acquired using standard mineral separation techniques at Simon Fraser University (Burnaby, BC), which include jaw crushing, pulverizing in a disk mill, and density separation using a Wilfley table and heavy liquids (methylene iodide). The zircons from the igneous samples were also magnetically separated using an LB-1 Frantz® Magnetic Barrier Laboratory Separator (only for igneous zircon). At the Boise State University Isotope Geology Laboratory (Boise, Idaho) zircon crystals were hand-picked from the heavy mineral fraction and annealed at 900°C for 60 hours in a quartz vessel in a muffle furnace. Crystals were then mounted in epoxy, and polished stepwise using silicon carbide films of 30, 15, 9, 3 and 1 µm to expose a medial section of each crystal, followed by polishing with a 0.3 µm alumina slurry. Cathodoluminescence imaging was performed to characterize the internal zoning of the zircon. The grains were checked for zoning, inclusions and cracks, which could complicate the analyses. Zircon crystals were analyzed by laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) using a

Thermo Scientific XSERIES 2 Quadrupole ICP-MS and New Wave Research laser ablation system. In-house analytical protocols, standard materials and data reduction software were used for acquisition and calibration of U-Pb dates and acquisition of a suite of high-field-strength elements (HFSE) and rare earth elements (REE). Zircon was ablated with a laser spot, 25 or 30 µm wide, during a 45 second analysis consisting of 15 seconds of gas blank and 30 seconds of ablation, which quarried a pit ~25 µm deep. For U-Pb and $^{207}Pb/^{206}Pb$ dates, instrumental fractionation of the background-subtracted ratios was corrected and dates were calibrated with respect to interspersed measurements of the zircon standard. For more complete details of the methodology, refer to Rivera et al. (2013). Future work will entail analyzing crystals requiring more precise ages (e.g., the youngest detrital zircon and igneous zircon); they will be plucked from the epoxy grain mounts and analyzed by chemical abrasion TIMS.

Pb Isotopic Analysis

The Pb isotopic compositions of single grains of galena, pyrite and pyrrhotite were analyzed by TIMS at the Boise State University Isotope Geology Laboratory in an attempt to constrain the age of formation of the Ruddock Creek Zn-Pb deposit. Purified Pb and U from single dissolved grains of galena, pyrite and pyrrhotite were loaded together with a silica gel–phosphoric acid emitter solution on single Re filaments. The Pb and U isotopic compositions were measured sequentially as Pb+ ions or UO_2+ ions on a mass spectrometer.

Preliminary Results

Field Mapping

Mapping the property and undertaking a detailed structural analysis resulted in a more complete understanding of the mesoscale structures that control the map-scale pattern of lithologies and the geometry of the Zn-Pb deposit. The mineralized outcrop pattern displays a complicated outline that defines a type 3 fold interference pattern (Ramsay, 1962) created by superposed folding with significantly thickened hinges and attenuated and dismembered limbs (Figure 3). This led to the conclusion that the metasedimentary rocks present on the property have indeed been subjected to at least three phases of ductile deformation and that the main mineralized zone (the E zone) is hosted within the hinge (trending 290° and plunging ~30°) of a property-scale fold, as was previously suggested by Fyles (1970). It is clear that the E zone occurs within the hinge of the large fold and has been structurally thickened (Figure 3). Conversely, the mineralized horizon has been substantially attenuated and dismembered within the folds limbs, and as such had been historically mapped as separate mineralized zones. Based on these finding, it was possible to begin predicting where the mineralized horizon would crop out in other parts of the property. Two new showings were identified during mapping. The S zone represents an extension of the upper limb of the overturned, recumbent D_2 fold that controls the map-scale geometry and the K zone represents an extension of the lower limb. These two new showings have helped confirm the working hypothesis that the geometry of the mineralized horizon, which serves nicely as a marker unit, is controlled by a map-scale type 3 fold interference pattern (Figure 3). All the mineralized showings (E, F, G, T, Creek, Q, U, R, S and K; Figure 3) appear to be confined to a stratigraphic interval associated with the calcsilicate gneiss. These map patterns, confirmed by the two new showings, suggest that there are prospective targets yet to be found on the property within the tectonically thickened hinges of F_2 folds to the west of the main E zone.

U-Pb Geochronology

Geochronological analyses, including complete U-Pb and trace-element LA-ICP-MS analyses, were carried out on 2 granitoid (Table 1) samples and 12 detrital zircon samples from the host metasedimentary units. A total of 1571 spots on detrital and igneous zircon grains was acquired. The detrital samples are grouped together based on the similarity of their age probability distribution peaks (Figure 4).

- Samples LT13-255, LT13-245, LT13-242, LT13-007B and LT13-249 have peaks that are typical of zircon derived from the Laurentian craton with their largest peaks at ca. 1800 Ma. These samples also have minor peaks at ca. 2550 to 2500 Ma and a number of smaller peaks between ca. 3000 and 2550 Ma. Very small, almost indiscernible peaks also occur between ca. 1600 and 1150 Ma.
- Samples LT13-250 and LT13-017 have a broad distribution of ages, as young as ca. 1100 Ma, with the largest age peaks from ca. 1800 to 1550 Ma. Minor probability age peaks are again found at ca. 2550 Ma, with a number of smaller peaks between ca. 3000 and 2550 Ma.
- Sample LT13-254 includes the oldest grains of all the detrital zircon samples, with a peak at ca. 3350 Ma. The largest peaks range from ca. 2100 to 1600 Ma. The youngest grains are ca. 1450 Ma.
- Sample LT13-263 has a similar probability plot to sample LT13-254. Most peaks range between ca. 1850 and 1600 Ma, with a smaller peak at ca. 2550 Ma.
- Samples LT13-297 and LT13-246 are two of the four samples with small populations of ca. 650 Ma grains. Both samples have large peaks at ca. 1000 Ma grains and only a few analyses that fall between ca. 2650 and 2500 Ma.
- Samples LT13-276 and LT13-026 have the youngest of grains. A single grain dated at ca. 560 Ma was recovered from sample LT13-276 and five grains between ca. 591 and 574 Ma were found in sample LT13-026. Both sam-

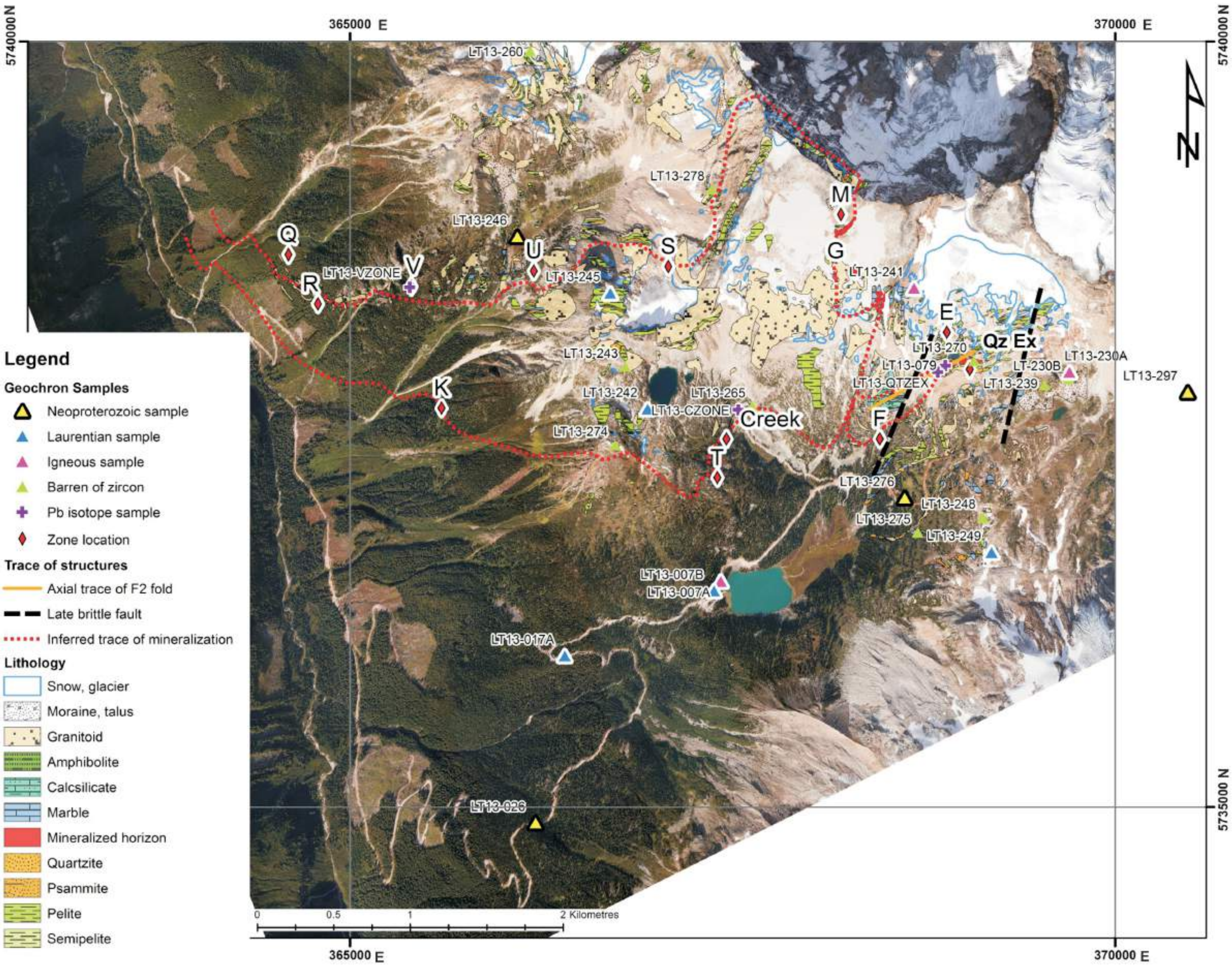

Figure 3. Geological map of the Ruddock Creek property (modified from Morris, 1965; Fyles, 1970), southern British Columbia, superimposed on a light detection and ranging (LiDAR) image (Eagle Mapping, 2012), including geochronology sample sites and lithology. Abbreviation: Qz Ex, quartz exhalite horizon.

ples have the largest peaks at ca. 650 Ma and do not contain zircon grains older than 1800 Ma.

The LA-ICP-MS data from the igneous lithologies, samples LT13-230 and LT13-241, suggest igneous crystallization occurred at ca. 103 and 63 Ma, respectively (Table 1).

Pb Isotopic Analysis

Galena, pyrite and pyrrohotite from eight massive sulphide samples were analyzed for their common Pb isotopic signatures. Galena grains were picked from samples from the E zone, Creek zone, V zone and Quartz exhalite horizon (Figure 3). Pyrite was picked from the Quartz exhalite horizon and pyrrohotite was picked from the V zone. Galena duplicates were analyzed for the Quartz exhalite horizon and Creek zone. Isotopically, there was very little difference between galena-pyrite and galena-pyrrohotite pairs. Plotting the Pb isotopic data on the 'shale curve' (Godwin et al., 1988; Nelson, 1991; Mortensen et al., 2006; Figure 5) provides a model age of the mineralization of ca. 530 Ma. The values from the eight analyses show slight variation, with the E zone and V zone having similar $^{207}Pb/^{204}Pb$ isotopic ratios and the Creek zone and Quartz exhalite horizon demonstrating similar $^{207}Pb/^{204}Pb$ isotopic ratios (Table 2).

Age Constraints for the Host Windermere Stratigraphy

The Ruddock Creek deposit has undergone a complex, penetrative deformation and polymetamorphic history, which relates to multiple tectonometamorphic events within the southern Canadian Cordillera. Ages of detrital zircon offer a geochronological fingerprint that reflects the age and distribution of continental basement from which the zircon was sourced (Ross and Parish, 1991). The age and chemistry of detrital zircon at the Ruddock Creek property can be used to infer the provenance of the grains, the majority of which are interpreted to be magmatic rocks with Laurentian heritage. The youngest ages of the detrital grains of zircon

Table 1. Summary of igneous samples' location, geological relationships and age, Ruddock Creek property, southern British Columbia.

Sample	Easting[1]	Northing[1]	Elevation (m asl)	Description	Age (Ma)
LT13-230A	5737794	369694	2127	Medium-grained granitoid. Concordant with D2 and folded by F3.	103.2 ±1.3
LT13-241	5738388	368685	2498	Crosscutting medium-grained granitoid, post-tectonic dike. Constrains the youngest age of deformation in the area.	62.93 ±0.6

[1] NAD 83, UTM Zone 11

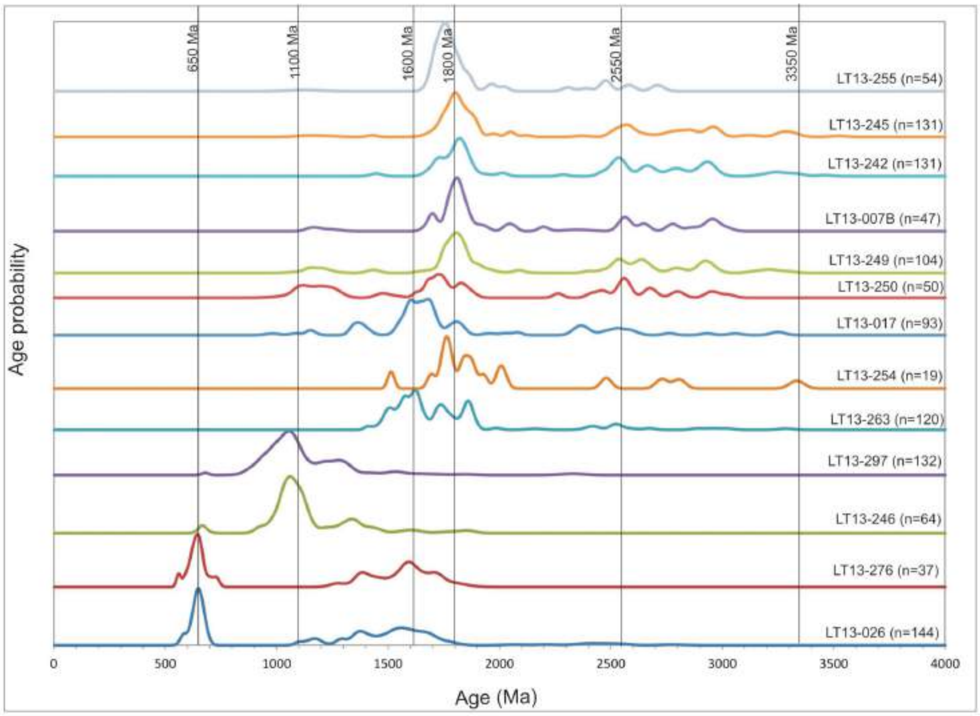

Figure 4. Normalized probability plot of 12 detrital zircon samples, Ruddock Creek property, southern British Columbia. Samples are grouped together based on similar probability peaks.

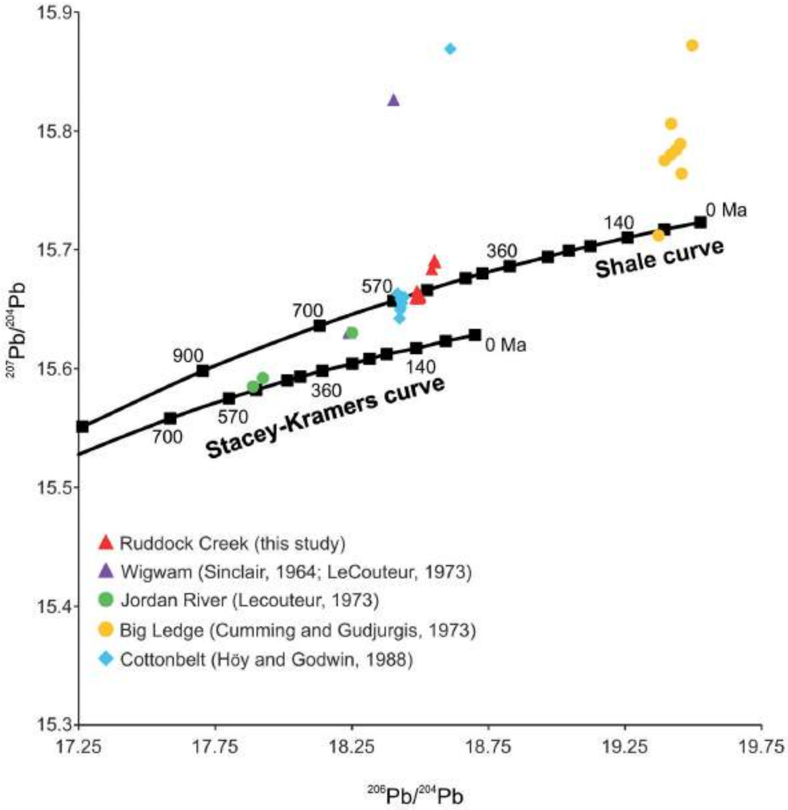

Figure 5. Lead isotopic data for sulphides from sedimentary exhalative (SEDEX)-type deposits (after Sinclair, 1964; Stacey and Kramers, 1975; Godwin et al., 1988; Nelson, 1991; Mortensen et al., 2006). The southern British Columbia Ruddock Creek deposit data (red triangles) plot on and just above the shale curve ca. 530 Ma.

Table 2. Lead isotopic data for the Zn-Pb horizon, Ruddock Creek property, southern British Columbia.

	Pb ratios				
Sample	208/206	207/206	208/204	207/204	206/204
Qtz ex galena 1	2.059968	0.846629	38.1063	15.6615	18.4986
Qtz ex galena 2	2.060209	0.846734	38.0994	15.6587	18.4932
Qtz ex pyrite	2.059462	0.846516	38.0981	15.6598	18.4992
V zone galena 2	2.058651	0.84577	38.1924	15.691	18.5523
V zone pyrrhotite	2.058658	0.84555	38.1983	15.6892	18.5551
Creek zone galena 1	2.060551	0.84729	38.0956	15.6649	18.4883
Creek zone galena 2	2.060024	0.847167	38.0771	15.6589	18.484
E zone galena 2	2.057998	0.845825	38.1598	15.6835	18.5423

Abbreviation: Qtz ex, Quartz exhalite

provide the maximum age of deposition for the individual sedimentary units.

The ages determined in this study carry with them important implications for the age of stratigraphy in the region, and allow for a comparison against stratigraphic ages previously determined for units within the Monashee complex to the south (Crowley, 1997; Millonig et al., 2012). The youngest detrital grains suggest that the maximum age of deposition in at least one sample at Ruddock Creek is ca. 560 Ma. Five grains in another sample have ages between ca. 591 and 574 Ma. Because it is possible that these young dates are inaccurate due to Pb loss or mixing with Cordilleran metamorphic rims, they should be considered suspect until more analyses can be carried out to confirm their legitimacy. Robust peaks from four samples occur at ca. 650 Ma. The youngest zircon in the other samples is >1000 Ma. The four youngest samples might suggest a stratigraphic facing toward the core of the fold with younger sedimentary rocks on the outside limbs of the fold and older rocks within the centre of the fold. If so, the detrital results suggest that the isoclinal, map-scale fold outlined by the Zn-Pb horizons, is an overturned, recumbent anticline as opposed to a syncline, as originally suggested by Fyles (1970).

Age Constraints for Deformation at the Ruddock Creek Property

Igneous sample LT13-230A is a grey, medium-grained granitoid, which is concordant with the penetrative transposition foliation and has been folded by the third phase of deformation. The geological features of sample LT13-230A are interpreted to indicate that this body intruded syn-D_2, and thus, its age of 103.2 ±1.3 Ma is interpreted to constrain, in part, the age of D_2 and the development of the transposition foliation in this area. Sample LT13-241 is from a highly discordant medium-grained granitic dike. The sample occurs structurally above the E zone and crosscuts the penetrative foliation and is unaffected by F_3 folds. Thus, it is considered to be post-tectonic and its age of 62.93 ±0.6 Ma is interpreted to constrain the end of the ductile deformation at the Ruddock Creek property.

Age and Deposit Model for the Zn-Pb Horizon

One of the most difficult issues to address regarding the Ruddock Creek property is what model best fits the deposit. Traditionally, it has been interpreted to be a SEDEX-type deposit, and the deposit does fit the SEDEX model in many ways. The map patterns, consistency of stratigraphic position and similar Pb isotopic signatures are all consistent with the mineralized horizon having been originally deposited as a continuous horizon by subseafloor dispersion of ore fluids along permeable strata within a single basin (Sangster, 2002). Furthermore, the principal ores are sphalerite and galena and there is evidence of rifting, indicated by the presence of amphibolite interlayered with the metasedimentary units. However, because of the metamorphic grade and pervasive ductile deformation, there is no remaining primary evidence of submarine venting of hydrothermal fluids or a growth fault. The lack of an identifiable proximal growth fault brings into question whether or not the deposit might be characterized as Lydon's (1995) vent-distal model, when no growth fault is present in the immediate vicinity of the deposit. The amount of calcareous stratigraphy hosting the Zn-Pb horizon at the Ruddock Creek property reinforces Sangster's (2002) suggestion that it is unlikely that newly deposited sediments are absolutely impermeable and that auriferous seafloor brines most likely sink into the underlying sediments. The massive sulphide mineralization at the Ruddock Creek deposit locally displays a gradational contact with the host calcsilicate units; this implies that the deposit can still be characterized as a syngenetic SEDEX type, rather than an epigenetic carbonate-replacement–type deposit. Höy (2001) suggested that the deposit be classified as a Broken Hill–type deposit. Broken Hill–type deposits are interpreted to be metamorphosed equivalents of SEDEX deposits (Sangster, 1990; Höy, 2001). The high base metal/iron sulphide ratio, the presence of Fe-rich sphalerite and fluorite, and a calcareous host to the mineralization typifies Broken Hill–type deposits (Höy, 2001).

Another aspect of the project that could use refinement is directly dating the mineralized horizon. The Pb isotopic data for the Ruddock Creek deposit sits on and just above and to the right of the shale curve at ca. 530 Ma (Figure 5). This corroborates well with the maximum age of deposition provided from the detrital zircon dates (i.e., ca. 560 Ma); however, more work is necessary to confirm both the age of the deposit and the maximum age of the host stratigraphy. Regardless, the very close similarity in Pb isotopic compositions from the various mineralized zones is interpreted to indicate that the zones are genetically related, and may have originated as one lithostratigraphic horizon prior to dismemberment by isoclinal folding and transposition. The slight variability in the Pb isotopic compositions of the different parts of the deposit most likely reflects the inhomogeneity of the depositional environment. Some variability in the measured Pb isotopic compositions within a single deposit should be expected. For instance, on the continental slope, in the deep-water realm, there are many inherent facies changes due to the underwater geomorphology (Hubbard et al., 2012), which implies that there would never be complete homogenization of the isotopic compositions of the source rocks, even in SEDEX deposits. Due to the abundance of Pb in the initial mineralizing system of the Ruddock Creek deposit, all of the Pb in the immediate vicinity of the deposit would be overwhelmed by the initial Pb in the deposit (Mortensen et al., 2006), and therefore would reflect the original Pb concentrations of the deposit-forming environment. There was very little variation in the Pb isotopic concentrations from the four mineralized zones, which suggests that all the zones were likely deposited at approximately the same time, all under the same environmental conditions.

Regional Implications for Other Zn-Pb Deposits

There are a number of stratabound Pb-Zn deposits in the southern Canadian Cordillera that may be related to the Ruddock Creek deposit, including the Big Ledge deposit, 60 km south of Revelstoke, the Wigwam deposit, 20 km southeast of Revelstoke, the Jordan River, deposit 24 km northwest of Revelstoke, and the Cottonbelt deposit, 50 km northwest of Revelstoke. The Pb isotopic data for the Ruddock Creek and Cottonbelt deposits suggest they may have formed at the same time during the Cambrian metallogenic event that is well documented in the Canadian Cordillera (MacIntyre, 1991). However, the stark differences in the lithostratigraphy hosting the two deposits argue against their being genetically related. Furthermore, the ca. 360 Ma age for the extrusive Mount Grace carbonatite (Millonig et al., 2012) currently situated beneath the Cottonbelt deposit brings into question the Cottonbelt deposit's ca. 570 Ma Pb model age, this coupled with the absence of any detrital zircon <560 Ma at the Ruddock Creek property, makes any correlation between the two deposits all the more difficult. Further afield, the lack of recent age constraints on the Big Ledge and Wigwam deposits, situated to the south and east, respectively, of the Monashee complex, make it difficult to address their temporal relationship to the other SEDEX-type deposits of the area. Whether or not basin development, and therefore syngenetic SEDEX deposit formation, had a long and protracted history in this region is still debatable.

Conclusions

The detrital zircon population from this study shows a temporal dichotomy. Four samples yielded a younger population of Neoproterozoic dates of ca. 650 Ma, with one analysis as young as ca. 560 Ma, and older grains include a peak at ca. 1100 Ma and reflect the typical Laurentian signatures that produce significant Meso- to Paleoproterozoic peaks at ca. 1500, 1700, 1800 and 2500 Ma. These data are consistent with the host lithologies of the Ruddock Creek deposit being part of the Windermere Supergroup, an interpretation previously made but never fully proven (Scammell, 1993). The ^{207}Pb/^{204}Pb model age of ca. 530 Ma provided by plotting the Pb isotopic data on the shale curve supports the idea that the Ruddock Creek mineralized horizon was deposited syngenetically with the metasedimentary host rocks. Even if the Pb isotopic model age is brought into question, the maximum age determined for the metasedimentary units that bound the mineralized horizon at the Ruddock Creek property has helped tighten the constraints on the age of deposition, which is no older than ca. 560 Ma.

The complicated structural history of the Ruddock Creek deposit makes detailed structural mapping essential for determining its geological history and evaluating its economic potential. Within the Selkirk allochthon, the first phase of deformation consisted of kilometre-scale southwest-vergent folds. The second phase of folding overturned the first phase and produced a penetrative transposition foliation and is characterized by northeast-vergent isoclinal folds. Development of the regional transposition foliation and subsequent overprint by D_3 deformation took place from ca. 136 to 57 Ma (Scammell, 1993), which correlates with the timing put forward in this research. Map patterns observed during this research have suggested that the mineralized horizon has been subject to all these phases of deformation. The fact that the deposit has been metamorphosed to upper amphibolite facies and polydeformed makes it very difficult to say with confidence what model the deposit would best fit. Based on the observations and data that were collected, the Ruddock Creek deposit seems to most closely fit that of a Broken Hill–type SEDEX deposit. Knowing what model can be applied to the deposit could help with future exploration for similar deposits, possibly even along the length of the Cordillera. The presence of the Ruddock Creek deposit within the Windermere Supergroup suggests that this succession of rocks is a viable exploration target.

Future work for the project includes the creation of a detailed geological map, possibly more detrital zircon analyses and Sm-Nd analyses of the mineralized horizon with hopes of directly dating the timing of ore genesis. Very few well defined ages have been produced for highly metamorphosed SEDEX-type deposits, provided that the Sm-Nd isotopic system has not been disrupted at the Ruddock Creek property, elucidating a Sm-Nd isochron. Testing both sphalerite and fluorite from the main mineralized zone, the E zone, could prove to be very instructive. Not only could this method of dating the mineralization help constrain the genetic model for ore deposition but it could also possibly provide a feasible method for dating highly metamorphosed SEDEX-type deposits.

The work included in this project is part of the senior author's master's thesis, which should be completed this summer.

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