Carbonate-hosted deposits (Mississippi Valley–type, magnesite, and REE-F-Ba) of the southeastern Canadian Cordillera: a review and isotopic data comparison

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Abstract: The Mississippi Valley–type, magnesite, and REE-F-Ba deposits in the southeastern Canadian Cordillera are in the weakly deformed/metamorphosed Paleozoic carbonate platform of the Rocky Mountains. Most are hosted in dolostones of the middle Cambrian Cathedral, upper Cambrian Jubilee, and Upper Devonian Palliser formations and spatially associated with hydrothermal dolomite. They occur along structurally controlled facies transitions between the shallow-water carbonate platform and deeper water basin rocks of the Paleozoic continental margin. Their location and morphology reflect episodic rifting along the Paleozoic margin. The carbonate protolith was replaced by fine-grained 'replacive dolomite' followed by several stages of coarser saccharoidal, sparry, and saddle dolomites and sulfides replacing dolostone and filling open spaces. The ⁸⁷Sr/⁸⁶Sr, δ^{18} O, δ^{13} C, and fluid-inclusion data are consistent with high-temperature fluids interacting with host rocks and show influence of adjacent or underlying siliciclastic rocks. The large range of δ^{34} S values of sulfides suggests that thermochemical sulfate reduction of seawater sulfate was the main sulfur-reducing process, but bacterial sulfate reduction also occurred locally. Lead isotopes suggest a mixing trend involving highly radiogenic and non-radiogenic end members. These observations are consistent with hydrothermal fluids replacing protoliths, precipitating sulfides, and possibly REE-F-Ba mineralization.

Résumé : Les gîtes de type Mississippi-Valley (M-V), de magnésite, de barytine, et d'ÈTR-F-Ba du sud-est de la Cordillère canadienne se trouvent dans les roches carbonatées de plate-forme légèrement déformées et métamorphisées du Paléozoïque, dans les montagnes Rocheuses. La plupart de ces gîtes sont encaissés dans des dolomies des formations de Cathedral (Cambrien moyen), de Jubilee (Cambrien supérieur) et de Palliser (Dévonien supérieur) et sont spatialement associés à de la dolomite hydrothermale. Ils se manifestent le long d'importantes transitions de faciès à contrôle structural entre les roches de plate-forme carbonatée d'eau peu profonde et celles de bassin d'eau plus profonde de la marge continentale du Paléozoïque. Leur emplacement et leur morphologie témoignent d'un rifting épisodique le long de la marge paléozoïque. Le protolite carbonaté a été remplacé par de la « dolomite de remplacement » à grain fin et ultérieurement par plusieurs générations de dolomite plus grossière à texture saccharoïde, spathique ou «en selle» et de sulfures, qui remplacent la dolomie et colmatent les espaces ouverts. Les valeurs de 87 Sr/ 86 Sr, δ^{18} O et δ^{13} C et celles tirées de l'étude des inclusions fluides sont compatibles avec l'interaction de fluides de haute température avec les roches hôtes, et révèlent l'influence de roches silicoclastiques adjacentes ou sous-jacentes. La large gamme de valeurs de δ^{34} S des sulfures suggère que la réduction thermochimique des sulfates de l'eau de mer était le processus principal de réduction du soufre, mais qu'une réduction bactérienne des sulfates est aussi survenue localement. Les isotopes du plomb suggèrent une tendance au mélange de membres extrêmes hautement radiogéniques et non radiogéniques. Ces observations sont conformes au remplacement des protolites par des fluides hydrothermaux, à la précipitation des sulfures et, possiblement, au dépôt de la minéralisation d'ÉTR-F-Ba.

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INTRODUCTION

Carbonate-hosted deposits in southeastern British Columbia include Mississippi Valley-type (MVT; Leach et al., 2005; Paradis et al., 2007), sparry magnesite (Simandl and Hancock, 1991, 1999; Simandl, 2004), rare-earth element (REE)-F-Ba (Green et al., 2017; Hoshino et al., 2017a, b; Akam et al., 2019), and barite-sulfide vein and replacement deposits (Paradis and Simandl, 2018), among others. In the southern Canadian Cordillera, these deposits are located along a series of tectonostratigraphic belts spanning the length of the Cordillera. Starting in the west, the Kootenay Arc of the Kootenay terrane consists of deformed and metamorphosed volcano-sedimentary rocks hosting numerous MVT and less abundant sedimentary exhalative (SEDEX) deposits (Fig. 1; Nelson et al., 2002; Paradis et al., 2006a). East of the Kootenay Arc are the less deformed and less metamorphosed platform sedimentary rocks of the Rocky Mountain foreland belt, which host numerous MVT and magnesite deposits, along with a REE-F-Ba deposit and rare SEDEX deposits (Dawson et al., 1991). Platform carbonate strata host the MVT, magnesite, and REE-F-Ba deposits, whereas the adjacent deep-water basin strata host the rare SEDEX deposits.

In this paper, we focus on carbonate-hosted deposits of the southern Rocky Mountains and report on the geological, mineralogical, and geochemical characteristics of MVT, magnesite, and REE-F-Ba deposits, and potential genetic links among them. These deposits are investigated by integrating detailed fieldwork with complementary petrography, mineralogy, stable- (i.e. O, C, S) and radiogenic- (i.e. Sr, Pb) isotope analyses, and fluid-inclusion studies. Stable and radiogenic isotope results are used to constrain the source reservoirs for S and Pb (and, by inference, other metals), and assess the geochemical processes related to mineralization. Pyrite Re-Os geochronology was attempted on selected deposits with moderate success; the results are presented briefly in the discussion and form the main topic of other publications (e.g. Hnatyshin, 2018; Paradis et al., 2020).

REGIONAL GEOLOGICAL SETTING

The carbonate-hosted deposits discussed in this paper are located in the southern Rocky Mountain foreland belt, along and east of the projection of the Cathedral Escarpment (Fig. 1). The strata in the Rocky Mountains are deformed into a thin-skinned thrust-and-fold belt that developed along a basal-detachment fault system, initiated by Late Jurassic to Paleogene eastward accretion of allochthonous terranes (Price, 1981, 1994; McMechan, 2012; Nelson et al., 2013). These strata represent the late Proterozoic to Middle Jurassic western margin of the North American Craton. Upper Proterozoic to lower Cambrian rocks of the Windermere Supergroup were deposited during intracontinental rifting (Price, 1994), followed by repeated platform-basin transition sequences in the middle Cambrian that formed along a fault-controlled, paleogeographic high known as the Kicking Horse Rim (Aitken, 1971, 1989), which corresponds approximately to the projection of the Cathedral Escarpment (Fig. 1) and other escarpments.

Several deposit types (MVT, SEDEX, vein and replacement Ba-Pb-Zn, magnesite, REE-F-Ba, and talc) occur along the Cambrian platform-basin transition (Simandl and Hancock, 1991; Simandl et al., 1992; Powell et al., 2006; McMechan, 2012; Paradis and Simandl, 2017, 2018, 2019). East of the projected western margin of the Kicking Horse Rim, middle to upper Cambrian, Ordovician, and Upper Devonian shallow-water platform carbonate rocks host MVT (e.g. Monarch and Kicking Horse, Boivin-Munroe-Alpine, Shag, Hawk Creek, and Oldman), magnesite (e.g. Mount Brussilof), and REE-F-Ba (e.g. Rock Canyon Creek) deposits (Fig. 1, 2; Table 1). West of the Kicking Horse Rim and the Cathedral Escarpment, deep-water basin rocks of the Chancellor Group include the Burgess Shale Formation and lesser accumulations of limestone and lenses of Mg- and Ba-rich chloritic rocks (Powell et al., 2006). This regional tectonosedimentary environment on the western continental margin was the depositional setting for Cambrian to Ordovician carbonate rocks of the Cathedral, Eldon, Stephen, and Jubilee formations (among others) and Middle to Upper Devonian carbonate rocks of the Cedared, Burnais, and Palliser formations. Middle Jurassic to Eocene Cordilleran orogenic tectonism later deformed, imbricated, and transported these sequences northeast (McMechan, 2012) to form the present-day Rocky Mountains.

GEOLOGY, MINERALOGY, AND PARAGENESIS OF SELECTED DEPOSITS

The geological descriptions that follow are based on our field observations and cited references. The mineralogy and paragenetic sequence of minerals are based on a suite of mineralized samples collected by S. Paradis and G. Simandl. Mr. C. Graf supplied samples from Shag. Some of the samples are described by Drage and Paradis (2018). The paragenetic sequences presented may not be representative of the entirety of each deposit. The principal characteristics of the carbonate-hosted deposits investigated in this study are presented in Table 1.

Monarch and Kicking Horse MVT deposits

Geology

The Monarch and Kicking Horse Zn-Pb (\pm Ag, \pm Cd) deposits are located along the Kicking Horse Rim (Fig. 1) on the north slope of Mount Stephen and the south slope of Mount Field, respectively, in Yoho National Park, British



Figure 1. Regional geological map of southeastern British Columbia showing locations of the carbonate-hosted deposits. Deposits identified by name are discussed in this paper; note that the Oldman deposit is located in Alberta. The projection of the Cathedral Escarpment corresponds approximately to the western margin location of the Kicking Horse Rim, a paleogeographic high that was initiated in the early middle Cambrian and persisted into the Ordovician (Aitken, 1971, 1989). Both features mark the change from shallow-water carbonate to the east and basin slope lithofacies to the west during the early Paleozoic. *Modified from* Katay (2017) with terranes *after* Cui et al. (2015).



Figure 2. Generalized stratigraphy of the Purcell anticlinorium and the Rocky Mountain foreland belt with locations of studied deposits indicated by stars (*modified from* Katay, 2017); Carb.: Carboniferous; Fm: Formation; Gp: Group; Miss.: Mississippian; Pensyl.: Pennsylvanian.

Columbia (Goranson, 1937). The deposits have been described by Allan (1914), Goranson (1937), Brown (1948), Ney (1954), and Evans et al. (1968), who provide invaluable information on underground workings, morphology of orebodies, and lithological relationships. Pană (2006) re-examined the geological and structural settings of the deposits to assess the influence of stratigraphic and structural controls on the mineralization. Vandeginste et al. (2007) investigated the geochemistry of the ore-forming fluids to constrain ore-forming processes.

The Monarch and Kicking Horse deposits include several orebodies in a thick succession of massive to thinly bedded, brecciated dolostone of the middle Cambrian Cathedral Formation (Fig. 2). Together, the Monarch and Kicking Horse deposits (BC MINFILE 082N 019 and 082N 020) produced 25 123 kg of Ag, 71 315 t of Zn, 46 218 t of Pb, and 9016 kg of Cd from 826 180 t of ore mined (British Columbia Geological Survey, 1993a, b). The orebodies, associated breccias, and dolomitized zones trend northward, parallel to the Kicking Horse Rim, forming north-northwest-aligned,

concordant sulfide lenses within a 60 m thick stratigraphic interval near the base of a brecciated, dolomitized alteration zone in the lower Cathedral Formation (Ney, 1957). The brecciated portion of the dolostone preferentially hosts the sulfide mineralization and consists of two rock types: a grey breccia and a white breccia (Ney, 1954). The grey breccia consists of light grey, angular to subangular and minor rounded fragments of variable size (≤ 1 cm to several metres in diameter) in a dark grey to black dolomite matrix (Ney, 1954). The white breccia comprises a stockwork of abundant coarse-grained white dolomite veins crosscutting fragments and a matrix of the light grey dolomite breccia. An unmineralized equivalent breccia is widespread in the Cathedral Formation (Ney, 1954).

Sulfide minerals consist of galena, sphalerite, and pyrite, and exhibit textures related to replacement and open-space filling (*see* section below and Drage and Paradis (2018)). Minor chalcopyrite, barite, and native silver were reported by Goranson (1937); however, these were not observed in our samples. Sulfide minerals are most commonly

Deposit (status¹)	BC MINFILE#	UTM	Deposit classification	Commodity	Formation/ Unit	Age of host rocks	Lithology	Mineralogy	Comments	References
Mount Brussilof (producer)	100WNL280	11 5627181 593120	Magnesite	Magnesite	Cathedral Formation	Middle Cambrian	dolostone	Magnesite, dolomite, pyrite, calcite, ankerite, quartz, and chlorite. Fersmite, tetrahedrite, malachite, phrogopite, talc, palygorskite, boulangerite, huntite, brucite, pentlandite, leuchtenbergite and muscovite were reported.	Magnesite forms layers, lenses, pods, and irregular masses replacing dolostone and limestone. It is typically sparry white or pale grey in colour and buff when weathered, and nearly monomineralic. It is cut by sparry dolomite zones.	Simandl and Hancock (1991); Simandl et al. (1992); Fritz and Simandl (1993); Simandl et al. (2019)
Monarch (past producer)	082N 019	11 5696188 539097	MVT	Zn, Pb (±Ag, ±Cd)	Cathedral Formation	Middle Cambrian	Massive to thin- bedded dolostone	Galena, sphalerite, and pyrite in gangue of dolomite and calcite. Minor chalcopyrite, barite, and native silver were reported.	Several concordant elongated cigar- shaped orebodies occur in the lower 125 m of the massive to brecciated, altered, light-grey dolostone. Most sulfides are disseminated in the cement of breccias or form veinlets and aggregates cutting cement and fragments.	Goranson (1937); Ney (1957); Pana (2006); Vandeginste et al. (2007); Drage and Paradis (2018) and Paradis (2018)
Kicking Horse (past oroducer)	082N 020	11 5697110 538434	MVT	Zn, Pb (±Ag, ±Cd)	Cathedral Formation	Middle Cambrian	Massive to thin- bedded brecciated dolostone	Galena, sphalerite, and pyrite (traces of chalcopyrite) in gangue of dolomite and calcite.	Same as above	Same as above

Table 1. Principal characteristics of carbonate-hosted deposits of southeastern British Columbia investigated in this study.

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	References	Bending (1979); Lenters (1981); Jensen (1991); Drage and Paradis (2018)	Gibson (1979a, b); Drage and Paradis (2018) (2018)	Gibson (1979a, b); Drage and Paradis (2018)
	Comments	Several known showings (e.g. C-3, BM, C-4, Red Bed) at different stratigraphic horizons at or near the contact with overlying argillaceous limestone. Sulfides form discontinuous, elongated lenses, pods, and thin layers replacing the dolostone, or occurring as disseminations, vug- and fracture-fillings, and breccia matrix.	Boivin, Munroe, and Alpine are three showings, collectively known as SOAB. Stratabound sulfides are disseminated in and replace a grey, supratidal, muddy to silty host dolostone. Zebra texture is common.	Same as above
(Mineralogy	Sphalerite, galena, and minor pyrite in a gangue of dolomite, quartz, and minor calcite.	Sphalerite, minor pyrite	Sphalerite, minor pyrite
	Lithology	Dolostone	Dolostone with fenestral porosity (filled by white sparry dolomite), zebra, lesser breccia	Dolostone
	Age of host rocks	Middle to upper Cambrian	Upper Devonian	Upper Devonian
	Formation/ Unit	Stephen, Eldon, and Waterfowl formations	Palliser Formation; lower (Morro) member	Palliser Formation; lower (Morro) member
	Commodity	Zn, Pb (±Ag)	Z	Zn
	Deposit classification	MVT	МУТ	MVT
	UTM	11 5610725 605203	11 5552197 636200	11 5547199 637740
	BC MINFILE#	082JNW002	082JSW011	082JSW012
	Deposit (status¹)	Shag (showing)	(showing)	Alpine (showing)

Table 1 (cont.). Principal characteristics of carbonate-hosted deposits of southeastern British Columbia investigated in this study.

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Age of host Lithology Mineralogy Comments References rocks	Upper Dolostone Sphalerite, minor Same as above Gibson (1979a, b); Devonian pyrite Drage and Paradis (2018)	UpperArgillaceousSphalerite, pyrite, and predominantly of almerstone, a galena (silver reported) in 	MiddleDolostone,Dolomite, fluorite, barite,Mineralization consistsGreen et al. (2017);Devoniandolomiticpyrite, quartz, K-feldspar,of disseminations,Hoshino et al.Imestone,calcite, apatite, REEveins, veinlets, andHoshino et al.Imestone,calcite, apatite, REEveins, veinlets, and(2017a, b); Akam et al.breccia andfluorocarbonates, andbreccia-matrix of pale(2018)breccia andREE phosphates, and purple fluoritewith associated barite(2018)silty,silty,fluorocarbonates andphosphates.gypsum	Upper Dolostone, Galena, pyrite, and Galena is the dominant Holter (1977); Devonian dolomitic sphalerite in a gangue sulfide. Sulfides occur Pana (2006) Imestone, of calcite (±dolomite, as breccia-veins, fractures, and vug limestone ±ankerite). fractures, and vug fillings.	eloped prospect: deposits on which exploration and development have progressed to a stage ommodities; showing: occurrences hosting minor in situ mineralization; prospect: occurrences
Formation/ Ag br Unit ro	Palliser Up Formation; Devo ower (Morro) member	McKay Group Up Cami	Cedared Mic and Burnais Devic formations	Upper Palliser Up Formation Devv	ed production; develop entially mineable comm
Commodity	Zu	Zn, Pb (±Ag, ±Au)	REE-F-Ba	Pb, Zn, Ag	but have recorder more of the pote
Deposit	MVT	TVM	REE-F-Ba	MVT	ently being mined imount(s) of one o
MTU	11 5543012 638345	11 5661756 567368	11 5564367 632300	11 5555350 662778	at are not curr imate of the a
BC MINFILE #	082JSW013	082N 021	082JSW018	A/A	icer: deposits the a reasonable est
Deposit (status ¹)	Boivin (showing)	Hawk Creek (developed prospect)	Rock Canyon Creek (prospect)	Oldman (showing)	¹ Past produ that allows a

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disseminated in the cement of the grey breccias or form veinlets and aggregates in the white breccias, but can also replace the host rock. Sulfide minerals are also present along bedding planes of the underlying black dolomitized limestone (Ney, 1957).

Mineralogy and paragenesis

Mineralized samples are breccias with subangular to rounded, irregular-shaped, grey dolostone fragments hosted in a white sparry dolomite (±calcite) cement (Fig. 3a). The fragments are light to dark grey and range from a few millimetres to several centimetres in diameter. They are commonly lined with pale yellow to dark brown sphalerite (±pyrite) and some are significantly replaced by honey-yellow sphalerite, minor pyrite, and galena. Sphalerite locally exhibits colloform textures when filling open spaces, and the white sparry dolomite cement crosscuts it locally. The coarse, crystalline, white sparry dolomite (±calcite) includes patches of disseminated galena, pyrite, and crystalline brown sphalerite. Fine- to coarse-grained pyritohedrons form aggregates and clusters (≤ 5 cm in diameter) in the white sparry dolomite and, locally, in the host dolostone.

The host rock, observed as patches and fragments within the mineralized breccia samples, consists of dark grey, fine- to medium-grained (0.02–0.15 mm in diameter), fabric-preserving dolostone that contains remnant allochems and inclusions of organic material (or insoluble residue). This dolostone is variably altered and partially to completely replaced by fabric-destroying, light grey dolomite identified herein as 'replacive dolomite' and characterized by fine- to medium-grained (0.01–0.1 mm in diameter), non-planar and planar-s dolomite crystals (Simandl et al., this volume).

An early phase of fine- to medium-grained (0.04-0.1 mm)in diameter), dark brown sphalerite is disseminated in the host dolostone and the light grey dolomite. A later phase of coarser (0.1-0.4 mm) in diameter), granular, honey-yellow to brown sphalerite replaces the host dolostone (Fig. 3b) along the perimeter of fragments and locally forms aggregates. Coarse-grained (0.5-1 mm) in diameter) sphalerite fills vugs and fractures, and commonly exhibits crustiform banding with colloform textures and coloured zonation from light brown to red (Fig. 3c).

Early very fine grained (<0.005 mm in diameter), rounded pyrite is disseminated in the host dolostone. Later finegrained (0.005–0.02 mm in diameter), subrounded pyrite is closely associated and intergrown with sphalerite. Coarser (0.05–0.2 mm in diameter) recrystallized pyrite overprints the host dolostone, grey dolomite, and sphalerite. Late pyritohedrons (0.8–2.5 mm in diameter) are disseminated in the white sparry dolomite cement of the breccias and veins, and line the walls of cavities. Galena forms irregular-shaped masses (≤ 1.6 mm in diameter) that fill open spaces and fractures and replace sphalerite, pyrite (Fig. 3d), and white dolomite. Fine- to medium-grained (0.02–0.2 mm in diameter) galena makes up less than 2% of the samples and is disseminated in the white sparry dolomite.

White sparry and saddle dolomite fills cavities and fractures, and forms veins with euhedral, coarse-grained crystals (0.8–1 mm in diameter) that crosscut breccia fragments and the matrix of the grey breccia. This dolomite is barren or hosts crystalline, subhedral to euhedral, coarse-grained (0.8–15 mm in diameter) sphalerite; fractured, colloform sphalerite; and other coarse-grained euhedral sulfide minerals.

Shag MVT deposit

Geology

The Shag deposit is located 41 km east of Invermere (Fig. 1) in platform carbonates along the Kicking Horse Rim (McMechan and Leech, 2011), approximately 3 km east of the transition to shale and limestone of the middle to upper Cambrian Chancellor Formation. It consists of 17 Zn-Pb (±Ag) showings in the Stephen, Eldon, and Waterfowl formations (Fig. 2; Jensen, 1991). The largest known showings are BM, Red Bed, and C-4, which are stratabound and occur at different stratigraphic levels. The BM showing occurs in a dolostone unit at the top of the Eldon Formation (unit C3 of Bending (1979)); the Red Bed showing occurs in dolostone at the top of the middle Cambrian Waterfowl Formation (unit C5 of Bending (1979)), just below the contact with the overlying argillaceous limestone of the Sullivan Formation (unit C6 of Bending [1979]); and the C-4 showing occurs in a dolostone unit of the Waterfowl Formation, stratigraphically below the Red Bed showing.

Sulfide minerals within the showings form discontinuous, elongated lenses, pods, and thin layers in the upper part of dolostone units, close to their contact with limestone units (Lenters, 1981). They occur as massive replacement of dolostone, disseminations within dolostone, vug- and fracture-fillings, and breccia matrix. The sulfide minerals are pale yellow to bright orange sphalerite, galena and minor pyrite in a gangue of dolomite, quartz, and minor calcite. The mineralogy is slightly different between showings (Drage and Paradis, 2018) and sulfide content seems to increase from the oldest (Stephen Formation) to the youngest (Waterfowl Formation) stratigraphic units.

Mineralogy and paragenesis

Sulfide minerals within the BM showing consist of disseminated yellow to reddish sphalerite in pale grey dolostone that consists of fine- to medium-grained (0.005–0.2 mm in diameter) subhedral dolomite crystals and contains stylolites and remnant allochems. Fine- to medium-grained (0.05–0.3 mm in diameter), subrounded quartz replaces the host dolostone, which contains disseminated, very fine grained pyrite. Yellow and red sphalerite occurs as medium- to coarsegrained (0.1–0.8 mm in diameter), irregular-shaped crystals that fill vugs and fractures and, with quartz, locally replace the host dolostone. The sparry, coarse-grained (0.6–1 mm in diameter) white dolomite intergrown with void- and fracture-filling quartz is typically not mineralized (except for disseminated pyrite grains and aggregates).

The Red Bed showing is characterized by the reddish colour of its sphalerite and the abundance of quartz (and lesser dolomite), which forms broadly irregular, altered and mineralized bands, layers, and veinlets in the dolostone [(Fig. 4a). The host dolostone is fine grained (approximately 0.1–0.2 mm in diameter) and is composed of equant dolomite grains with minor microcrystalline quartz; locally, remnants of ooids are visible. Quartz forms aggregates of microcrystalline to medium-grained (0.04–0.5 mm in diameter), non-oriented, interlocking grains with minor dolomite. Sphalerite is granular, coarse-grained (0.5–1 mm in diameter), shows colourless to dark orange zonation in plane-polarized light (Fig. 4b), and fills open spaces and replaces the host dolostone. Sphalerite alters to smithsonite along the grain boundaries, resulting in irregularly shaped grains. Dolomite forms anhedral to subhedral individual crystals (<0.1 mm in diameter) disseminated in the quartz-rich bands and layers, and aggregates of grains also form patches and lenses. Finegrained (0.02–0.04 mm in diameter), irregular-shaped pyrite



Figure 3. Mineralization from the Monarch and Kicking Horse Mississippi Valley–type deposits. **a)** Hand sample from the Kicking Horse deposit showing a breccia cemented by white sparry dolomite cement. Note that sphalerite and pyrite completely or partially rim the dolostone fragments. Photograph by S. Paradis. NRCan Photo 2020-112. **b)** Photomicrograph (plane polarized light: PPL) of intergranular brown sphalerite in the host dolostone. **c)** Photomicrograph (PPL) of a colloform sphalerite exhibiting colour zonation adjacent to white sparry dolomite. **d)** Photomicrograph (reflected light) showing galena replacing pyrite and sphalerite; Dolm: dolomite; Gn: galena; Host Dols: host dolostone; Py: pyrite; Sph: sphalerite.





occurs as disseminations. Galena, locally altered to cerussite, forms large, irregular-shaped masses (5–8 mm long) that crosscut and replace the host dolostone.

Intense replacement of the host dolostone by yellowish granular sphalerite, quartz, galena, and white to pale grey sparry dolomite is characteristic of the C-4 showing (Fig. 4c), which consists of massive aggregates of granular sphalerite that form broad bands and patches in a matrix of microcrystalline quartz, dolomite, and minor pyrite and galena (Fig. 4d). Two generations of quartz are observed: 1) a microcrystalline quartz intergrown with sphalerite and 2) irregular-shaped, fine- to medium-grained (0.2–0.5 mm in diameter), transparent crystals crosscut or intergrown with sphalerite. Most sphalerite occurs as equant, granular, medium-sized (approximately 0.25 mm in diameter), pale brown grains that form clusters or bands and replace the host dolostone. Large euhedral crystals of pale yellow sphalerite (≤ 1 cm in diameter) and clots of galena (approximately 0.8 mm long) are observed sporadically through the sample. Pyrite is minor in C-4, where it occurs as fine, subhedral, disseminated grains throughout the quartz-dolomite assemblage and also forms clusters (0.4 to 2 mm in size) of rounded grains locally replacing sphalerite. Minute (< 0.005 mm) pyrite is also present as inclusions in sphalerite, suggesting that pyrite formed before, during, and after sphalerite mineralization. Galena is concentrated in the quartz-dolomite zones, where it occurs as interstitial, irregular-shaped grains (0.01–0.03 mm in diameter) and is locally associated with sphalerite and pyrite.

Hawk Creek MVT deposit

Geology

The Hawk Creek Zn-Pb (\pm Ag, \pm Au) deposit is in Kootenay National Park, approximately 46 km south-southeast of the town of Field, British Columbia. It is located along the carbonate platform-to-basin facies transition (Fig. 1) and is hosted in thin-bedded grey argillaceous limestone and argillite of the upper Cambrian to Ordovician McKay Group (Fig. 2). Strata range from gently dipping to horizontal and are cut by a northwest-trending shear zone that likely extends laterally (Henderson, 1953). Mineralization exposed at surface forms an irregular-shaped cylindrical area, approximately 15 m wide and 75 m long (Henderson, 1953; Grieve and Höy, 1981). It is confined to one stratigraphic horizon, a favourable dolomitized limestone, and mineralization is localized around a shear zone. Although the shear zone extends out of this favourable bed, the mineralization does not, implying that mineralization is most likely lithologically controlled (Henderson, 1953).

The sulfide minerals present at Hawk Creek consist predominantly of two types of sphalerite: 1) a massive, very fine grained, honey-yellow sphalerite (Sph 1) that replaces the fine-grained grey limestone to dolomitic limestone (Fig. 5a) and 2) a dark brown, crystalline sphalerite (Sph 2) that is found within the white calcite veins, stringers, and vugs (Fig. 5b). Fine-grained pyrite is uncommon; where present



Figure 5. Samples of mineralization from the Hawk Creek deposit. **a)** Hand sample of massive aggregate of very fine grained, honey-yellow sphalerite (Sph 1) and coarser grained galena with calcite filling spaces between the sulfide minerals. Photograph by S. Paradis. NRCan Photo 2020-115. **b)** Hand sample of massive aggregate of dark brown sphalerite (Sph 2), galena, and coarse calcite. Photograph by S. Paradis. NRCan Photo 2020-116. **c)** Photomicrograph (plane polarized light) showing that replacement of the host carbonate rocks by light to dark brown massive and colloform sphalerite (Sph 1) is pervasive but locally leaves irregular patches of fine crystalline, grey dolomite (Dolm 1) and coarse-grained saddle dolomite (Dolm 2) that fills fractures and voids. **d)** Photomicrograph (reflected light) of sample in which galena forms irregular shaped crystals that mostly replace sphalerite along grain boundaries or extensively throughout it; Cc: calcite; Dolm: dolomite; Gn: galena; Py: pyrite; Sph: sphalerite.

it is associated with the dark brown sphalerite. Galena forms irregular patches (Fig. 5b). Silver content is reported by Richmond (1930); however, quantities are negligible.

Mineralogy and paragenesis

The massive, very fine grained, honey-yellow sphalerite (Sph 1) pervasively replaces the host carbonate rocks, though irregular patches of fine, crystalline, grey dolomite (Dol 1) are observed locally (Fig. 5c). Fractures and voids are filled with coarse-grained (0.8–3 mm in diameter) saddle dolomite (Dol 2; Fig. 5c). The saddle dolomite phase has planar-s grains and is barren of sulfide minerals with the exception of trace euhedral pyrite. Blocky, white, coarse crystalline (0.4–8 mm in diameter) calcite cement forms irregularly shaped crystals in veins, voids, and, locally, interstitial to various phases of dolomite and dark brown, coarsely crystalline (2–4 mm in diameter) Sph 2.

Irregular-shaped galena patches (0.02–5 mm in diameter) commonly replace sphalerite (Fig. 5d), either pervasively or along grain boundaries. Galena also fills open spaces and fractures within or crosscuts the phases of dolomite and white calcite, and rarely replaces the dolomite. Subhedral pyrite forms aggregates (up to 5 mm across) and massive to disseminated bands (up to 5 mm wide), which cross-cut sphalerite, galena, and the various phases of dolomite. Alteration of the sphalerite to smithsonite occurs in minor to trace amounts (<2 volume %). The elongate smithsonite crystals are generally disseminated and locally form mats.

Boivin, Munroe, and Alpine MVT deposits

Geology

Boivin, Munroe, and Alpine are three stratabound Zn sulfide deposits, collectively known as 'SOAB', located approximately 75 km northeast of Cranbrook, British Columbia (Fig. 1). The deposits form a north-northwest to south-southeast linear trend in the overturned limb of an east-verging asymmetrical anticline in the Upper Devonian Morro Member of the Palliser Formation. Major westward-dipping thrust faults have positioned these Devonian rocks above Mississippian carbonate rocks and below Cambrian to Ordovician strata (Gibson, 1979a, b). These deposits were mapped by Gibson (1979a, b) and drilled in 1976 by Silver Standard Mines Ltd.; however, little other work has been done since.

Mineralization is hosted in a dark grey, supratidal, muddy to silty dolostone with fenestral features filled by medium grey to white sparry dolomite. Alternating elongated patches of white sparry dolomite, host dolostone, and sulfide aggregates form a zebra texture (Fig. 6a). Remnants of bioclasts are also observed in the dolostone. The dolostone is overand underlain by what has been interpreted as a subtidal limestone (Gibson, 1979b), but limited field exposure has precluded determining if it is the same folded bed or two different ones.

Sulfide mineralization at all showings is identical and consists predominantly of sphalerite with lesser pyrite and rare galena. Mineralization replaces the grey, supratidal, muddy to silty host dolostone and consists of pale yellowish to orange sphalerite disseminations and aggregates forming bands and layers that alternate with elongate voids filled with white sparry dolomite, accentuating the zebra appearance. Sphalerite is also disseminated throughout the dark grey host dolostone, occurring as large yellow grains in vugs also containing saddle dolomite and calcite.

Paragenesis

The host dolostone is dark grey, fine to medium grained, crystalline (0.02–0.2 mm in diameter), and forms irregular patches of nonplanar or planar-e to planar-s crystals (Fig. 6b). Interstitial organic material (and insoluble residue) between dolomite crystals is common.

White to light grey saccharoidal dolomite (0.2–2 mm in diameter) replaces the host dolostone. The saccharoidal dolomite crystals are planar-e to planar-s and contain minor interstitial organic matter. Medium-grained (0.1–0.4 mm in diameter), irregular-shaped, intergranular sphalerite is present in the host dolostone, but most sphalerite mineralization occurs in the saccharoidal dolomite as aggregates of equant, granular, honey-yellow to brown, 0.2 to 2 mm grains (Fig. 6b). White, coarse to very coarse crystalline (0.5–4 mm in diameter) saddle dolomite and calcite fill open spaces in the host dolostone and saccharoidal dolomite. The white saddle dolomite is mostly unmineralized, although it locally includes medium- to very coarsely crystalline (0.1–1.5 mm in diameter) sphalerite in open spaces that were subsequently filled by calcite.

Trace pyrite is disseminated within the host dolostone as fine (0.01–0.03 mm in diameter), anhedral to subhedral grains. Locally, pyrite lines sphalerite grain boundaries or is replaced by sphalerite.

Oldman MVT deposit

Geology

Oldman is a stratabound Pb-Zn-Ag deposit hosted in the upper part of the Upper Devonian Palliser Formation in southwestern Alberta on the eastern slope of Mount Gass, near the British Columbia–Alberta border (Fig. 1, 2).

The host dolostone contains disseminated pyrite, sphalerite, and galena, and is cut by barren and mineralized (pyrite, sphalerite, galena) white calcite (±dolomite, ±ankerite) veins, limonite-rich veinlets, and fault gouges parallel to and crosscutting bedding.



Figure 6. Mineralization from the Munroe deposit. **a)** Hand sample with zebra-stripe texture created by the alternating, irregular, and discontinuous bands of dark grey dolostone with patches and lenses of light grey saccharoidal dolomite rich in sphalerite, and white sparry dolomite lenses. Photograph by S. Paradis. NRCan Photo 2020-117. **b)** Photomicrograph (plane polarized light) showing irregular patches of nonplanar or planar-e to planar-s dolomite crystals, coarser grained saccharoidal dolomite crystals, and irregular-shaped intergranular sphalerite; Dolm: dolomite; Host Dols: host dolostone; Sacch Dolm: saccharoidal dolomite; Sph: sphalerite.

Galena is the dominant sulfide mineral at Oldman and is present as disseminations in the dolostone and as coarsegrained crystals in calcite veins (Fig. 7a). Sphalerite occurs as disseminated, equant, dark brown grains that are interstitial to the subhedral to slightly interlocking, equant dolomite grains of the host dolostone. Sphalerite also forms yellow to brown replacement patches and occurs as open-space filling. Sphalerite is accompanied by fine-grained pyrite (<0.04 mm in diameter) and local galena.

Mineralogy and paragenesis

The host dolostone is dark grey and consists of equant, subhedral to slightly interlocking, medium-grained dolomite crystals (0.1–0.2 mm in diameter). The dolomite typically has irregular grain boundaries and contains up to 30 volume % microscopic fluid inclusions and semi-opaque inclusions of possible organic material. The dolostone is locally brecciated into fragments 0.5 to 2 cm in diameter that show minor local replacement by sphalerite and pyrite.

Pyrite occurs as fine to coarse grains (<0.02–0.6 mm in diameter) disseminated throughout the dolostone or associated with sphalerite. Replacement sphalerite is yellow to brown and forms patches of granular aggregates of fine to coarse grains (0.04–0.8 mm in diameter) or occurs as disseminated, equant dark brown grains, interstitial to the subhedral to slightly interlocking, equant grains of the host dolostone (Fig. 7b). Open-space–filling sphalerite is medium to coarse grained (0.5–2.5 mm in diameter), with colloform textures (Fig. 7c, d) that typically surround the host dolostone fragments.

Sphalerite and pyrite are locally fractured, indicating that brecciation postdates sulfide mineralization. Based on the observed relationships, it is likely that pyrite formed first and continued to precipitate while sphalerite precipitated, followed by brecciation of both. Galena is the latest sulfide mineral to precipitate, and occurs mostly as large, interstitial masses filling spaces and fractures, forming veins, and locally replacing dolostone, pyrite, and sphalerite.

Mount Brussilof magnesite deposit

Geology

The Mount Brussilof sparry magnesite deposit is located along the Kicking Horse Rim, approximately 82 km northeast of Invermere, British Columbia (Fig. 1), and is currently the only magnesite mine operating in Canada. In 2018, annual magnesite production was approximately 230 kt (Katay, 2019). The calcined product typically contains more than 97% MgO (Baymag, 2020). The stratigraphy of the Mount Brussilof deposit area and its geology are summarized in Simandl and Hancock (1991). The deposit is hosted by shallow marine carbonate rocks of the middle Cambrian Cathedral Formation east of the projection of the Cathedral Escarpment, and the magnesite forms layers, lenses, pods, and irregular masses. The favourable, stratabound, magnesite-bearing horizon has been traced intermittently for more than 12 km along strike (Simandl and Hancock, 1991; Simandl et al., 1992; Fritz and Simandl, 1993). In summary, the unmineralized Cathedral Formation consists mainly of fine-grained, massive or laminated dolostone interbedded with limestone. The dolostone contains well-preserved sedimentary and diagenetic textures and is locally brecciated and cemented by sparry white dolomite. Parts of the Cathedral Formation are entirely altered to sparry magnesite, which



Figure 7. Mineralization from the Oldman deposit. **a)** Hand sample of a galena-calcite (±dolomite) vein. Photograph by S. Paradis. NRCan Photo 2020-118. **b)** Photomicrograph (plane polarized light: PPL) of medium-grained dark brown sphalerite interstitial to dolomite. **c)** Photomicrograph (PPL) showing colloform sphalerite exhibiting colour zonation filling open spaces. Smaller grains are interstitial to or replace the dolomite. **d)** photomicrograph (PPL) of colloform sphalerite exhibiting colour zonation along the edges of a cavity filled by calcite; Cc: calcite; Dolm: dolomite; Gn: galena; Host Dols: host dolostone; Sph: sphalerite.

is of economic interest and is separated from limestone by light grey, massive dolostone. The contacts between sparry carbonate rocks (dolomite or magnesite) and the fine-grained dolomite are sharp and either concordant or discordant.

The magnesite is typically sparry, white or pale grey on a fresh surface, buff when weathered, and nearly monomineralic; individual crystals commonly measure 0.3 to 3 cm in diameter (Fig. 8a). The main gangue minerals (i.e. dolomite, calcite, pyrite, quartz, and clay) are disseminated within the magnesite ore, and infill fractures and vugs (Simandl and Hancock, 1999). Locally, pale grey and white magnesite occurs as alternating discontinuous layers or lenses (approximately 5 mm wide) within the white magnesite forming a zebra texture. In such 'zebra rock', magnesite is generally finer grained (0.2–4 mm in diameter) and the grey layers contain more opaque microscopic inclusions than white sparry magnesite. Sparry magnesite appears to replace the fine-grained (<0.1 mm particle size), grey dolostone host, which in turn postdates limestone. Pyrite is common as disseminations in fine-grained and sparry dolomite; however, it also occurs as irregular veinlets, pods, and pyritohedrons in sparry dolomite and magnesite. Pale pink, green, and brown mica, magnesium-rich chlorite, and palygorskite/ attapulgite (commonly referred to as 'mountain leather') are also present at Mount Brussilof. Boulangerite, chalcocite, huntite, and brucite were reported by G.P.E. White (unpub. rept., 1972). Niobium-, REE-, beryllium-, and lithium-bearing minerals such as fersmite ([Ca,Ce,Na] [Nb,Ta,Ti]₂[O,OH,F]₆; Simandl et al., 2019), niobiumbearing rutile, goyazite (SrAl₃[PO₄][PO₃OH][OH]₆), and euclase (BeAlSiO₄[OH]) were also recognized as late vug



Figure 8. Mineralization from the Mount Brussilof magnesite deposit. **a)** Coarse-grained sparry magnesite crystals in hand sample. Photograph by S. Paradis. NRCan Photo 2020-119. **b)** Field exposure of white sparry dolomite vein crosscutting grey magnesite ore. Photograph by S. Paradis. NRCan Photo 2020-120. **c)** Photomicrograph (plane polarized light) of a fersmite crystal in sparry dolomite; Dolm: dolomite; Frs: fersmite.

fillings at Mount Brussilof. Lithium-bearing micas are disseminated in late sugary dolomite and form pods in sparry magnesite, or fill vugs, where they may postdate sparry dolomite. In some cases, sparry dolomite zones crosscutting sparry magnesite contain pods or cavities with REE, berylium, and niobium minerals. (Fig. 8b; Simandl and Hancock, 1991).

Mineralogy and paragenesis

The relationship between magnesite and sparry dolomite is covered in the previous section and in detail by Paradis and Simandl (2018), and the relationships between fersmite, sparry dolomite, and sparry magnesite are the subject of a paper by Simandl et al. (2019). In summary, white, medium to very coarse crystalline (0.1–10 cm long) sparry dolomite forms crosscutting veins and fills vugs within the magnesite (Fig. 8b) and the fine-grained dolostone host. In the area of the Mount Brussilof deposit, an irregular, now mined out, dolomite pod or pocket (>10 m in longest exposed dimension) contained traces of black, euhedral fersmite (<0.5 to >10 mm in length), filling open spaces within the white sparry dolomite (Fig. 8c). Fersmite is commonly fractured and Simandl et al. (2019) locally observed a late minor stage of dolomite filling the fractures across the fersmite crystals. Euhedral euclase, goyazite, and micas were found as open-space fillings in the general area of the mine.

Fine-grained, pale green, magnesium-rich chlorite is the main constituent (>95% modal) of an approximately 0.2 to 0.5 m thick planar feature that crosscuts the magnesite deposit. It contains traces of fine-grained euhedral pyrite; an elongated, fine- to medium-grained (0.02–0.2 mm in diameter); high-relief mineral (probably rutile); and a very fine grained, zirconium-rich phase (either zircon or baddeleyite).

Rounded, fine- to medium-grained (0.02-0.1 mm)in diameter) pyrite is disseminated in trace amounts throughout the host dolostone and magnesite. Medium- to coarse-grained (0.2-0.5 mm) in diameter), subhedral to euhedral pyrite forms aggregates, stringers, and disseminations that replace and crosscut the magnesite. Locally, pyritohedrons (0.1-3 cm) in diameter) are also disseminated in the magnesite or in sparry dolomite.

Two hypotheses may explain the origin of magnesite: 1) a diagenetic process whereby magnesite forms by in situ recrystallization of a magnesium-rich sedimentary precursor, or 2) a hydrothermal process whereby sparry magnesite replaces fine-grained dolomite by interaction with magnesium-rich hydrothermal fluids (Paradis and Simandl, 2018). The presence of fersmite and other exotic minerals in sparry dolomite within the magnesite ore can be explained by Alpine cleft-type mineralization (Simandl et al., 2019). Discordant, thin, and planar Mg-chlorite rich zones postdate formation of the sparry magnesite and sparry dolomite, but its age relationship with fersmite is not established.

Rock Canyon Creek REE-F-Ba deposit

Geology

The Rock Canyon Creek REE-F-Ba deposit is located approximately 90 km northeast of Cranbrook, British Columbia (Fig. 1), along the same trend as the Munroe, Boivin, and Alpine MVT deposits in the footwall of the northwest-southeast Munroe Lake thrust, which divides the Main Ranges from the Front Ranges of the southern Canadian Rocky Mountains (Mott, 1989). The Rock Canyon Creek deposit is hosted by Middle Devonian carbonate rocks of the Cedared and Burnais formations (Fig. 2), which consist mainly of dolostone, dolomitic limestone, carbonate breccia, and laminated silty calcareous gypsum (Pell and Hora, 1987; Green et al., 2017).

A zone of dolostone-fragment crackle breccia appears to control REE-F-Ba mineralization, and forms a steeply dipping, stratabound, tabular body or set of lenses. This crackle breccia extends 1200 m along strike, subparallel to the contact of the Cedared and Burnais formations with the overlying argillaceous lime mudstone of the Maligne Formation (Green et al., 2017; Akam et al., 2019).

Mineralization forms breccia-matrix, veins, veinlets, and disseminations (Green et al., 2017). Minerals identified in the main mineralized zone are dolomite, fluorite, barite, pyrite, quartz, K-feldspar, calcite, porous apatite, REE fluorocarbonates, and REE phosphates (Fig. 9a, b, c; Hoshino et al., 2017a, b; Akam et al., 2019). The main REE fluorocarbonates (Fig. 9c) are bastnäsite ([Ce,La,Nd] CO_3F), parisite (Ca[Ce,La]₂[CO₃]₃F₂), and synchysite (Ca[La,Ce,Nd][CO₃]₂F), and the main REE phosphates are monazite ([Ce,La,Nd,Th]PO₄]) and crandallite group minerals (Hoshino et al., 2017a, b; Akam et al., 2019). Dolomite, barite, and at least three generations of fluorite are the main gangue minerals.

In addition, Pell (1994), Zhu (2000), and Samson et al. (2001) describe boulders of massive fluorite containing REEs and aluminofluoride minerals, found near the southeastern part of the deposit.

Mineralogy and paragenesis

Fine-grained dolostone (dolomitized limestone) hosts the mineralization, which is controlled by breccia and fracture zones. Coarse planar-s dolomite is probably the oldest hydrothermal mineral at Rock Canyon Creek and precedes fluorite and barite, which both enclose zoned euhedral crystals of ferroan dolomite. The relationship between fluorite and barite is texturally complex; where the relationship is clear, barite postdates fluorite. Vestiges of euhedral K-feldspar crystals, partially replaced by fluorite and barite, were identified in thin sections and confirmed using scanning electron microscopy. Quartz is a relatively minor constituent (<1%) of the mineralized rock, occurring predominantly as subhedral to euhedral grains (0.05–0.2 mm in diameter) in fluorite veinlets, and less commonly in vestiges of K-feldspar.

Coarse, prismatic synchysite crystals (0.04–0.06 mm in diameter) probably co-precipitated locally with fluorite and may be the same age as the euhedral ferroan dolomite. Most of the finer grained REE minerals (<0.005 mm) are disseminated or fill microfractures in sparry (ferroan) dolomite, fluorite, and barite. Fine-grained REE fluorocarbonates (mainly bastnäsite) are intergrown with monazite (Fig. 9c).

There are at least three textural varieties of pyrite, including the oldest, a fine-grained pyrite (0.008-0.04 mm in diameter) disseminated in dolostone vestiges, sparry dolomite, fluorite, and barite. Pyrite also fills fractures, replaces fossils, and forms pyritohedrons. Euhedral pyritohedrons (approximately 0.15-0.18 mm in diameter) are the latest generation of pyrite and contain inclusions of REE fluorocarbonates, ferroan dolomite, and other minerals near their core. Near their rims, these pyritohedrons are typically inclusion free and are interpreted to be of metamorphic origin; therefore, based on available data, REE mineralization is older than the latest pyrite generation (i.e. pyritohedrons) and of the same age or younger than euhedral ferroan dolomite, fluorite, and barite. Calcite is the latest carbonate to precipitate, being most abundant in the near-surface environment (less than 40 m from the surface).

METHODS

To constrain the nature of the ore-forming elements and processes related to sediment-hosted mineral deposits, a variety of petrography and in situ geochemical and isotopic methods have been applied or are in progress (*see* Paradis and Simandl (2018) for more information).



Figure 9. Mineralization from the Rock Canyon Creek REE-F-Ba deposit. **a)** Large, euhedral crystals of barite in a purple fluorite vein cutting altered dolostone in a drill-core sample (DDH-09-01 at 38.7 m). Note the fine fluorite veinlets and aggregates in the dolostone. Photograph by S. Paradis. NRCan Photo 2020-121. **b)** Drill-core sample (DDH-09-14 at 5.8 m) of altered dolostone crosscut by veins of purple fluorite and carbonate rocks and fine veinlets of pyrite. Pyrite also occurs as euhedral crystals in dolostone. Photograph by S. Paradis. NRCan Photo 2020-122. **c)** Backscattered electron image of the mineral assemblage from REE-F-Ba mineralization. Minerals identified in this image are ferroan dolomite, fluorite, pyrite, and REE-bearing fluorocarbonates, bastnäsite, and synchysite.

Oxygen and carbon isotopes

Representative samples of carbonate rocks from unaltered host rocks, replacive dolomitized carbonate rocks (i.e. 'replacive dolomite'), and mineralization (i.e. sparry, saddle, and ferroan dolomite) for each deposit were selected and analyzed (147 analyses total). Pure carbonate samples (10–100 mg) were obtained by microdrilling at the Geological Survey of Canada and analyzed at the Ján Veizer Stable Isotope Laboratory (formerly G.G. Hatch), University of Ottawa, Ontario, using a Thermo Finnigan GasBench coupled to a Delta Plus XP IRMS. Additional analyses were done at the Stable Isotope Geochemistry Laboratory (Delta-Lab) of the Geological Survey of Canada in Quebec City.

Ratios were determined on evolved CO_2 gas released from carbonate minerals by reaction with anhydrous phosphoric acid (at 25°C for calcite and 50°C for dolomite). Oxygen isotope values for dolomite and calcite were corrected using phosphoric acid fractionation factors (Kim and O'Neil, 1997; Sharma et al., 2002). Results are reported in conventional per mil notation (‰) relative to the Vienna Pee-Dee Belemnite (VPDB) standard. Accuracy of the analyses was $\pm 0.2\%$ for $\delta^{18}O_{VPDB}$ and $\pm 0.1\%$ for $\delta^{13}C_{VPDB}$, and the analytical precision was better than $\pm 0.1\%$ for $\delta^{18}O$ and $\delta^{13}C$.

Strontium isotopes

Strontium isotope analyses of 31 carbonate rocks were carried out at the Pacific Centre for Isotopic and Geochemical Research (PCIGR), The University of British Columbia, Vancouver, Canada. Approximately 100 mg of pure carbonate phases were obtained by microdrilling at the Geological Survey of Canada. Typically, splits of powdered samples used for C and O isotope analyses were also analysed for Sr isotope analyses. The powdered rock sample (approximately 100 mg) was weighed into a 15 ml Savillex vial, initially dissolved in 1 ml of 15M HNO3 and 10 ml of 29M HF and heated at 130°C for 36 to 48 h. The samples were then dried, dissolved in 10 ml of 6N HCl, and heated at 120°C for 12 h. After drying a second time, the samples were redissolved in 1 ml of 2M HNO3 and loaded onto a prepared Sr resin column. The column was rinsed four times with 0.1 ml 2M of HNO3, once with 1 ml of 7M HNO3, and two more times with 0.1 ml of 2M HNO₃. The Sr fraction was eluted with 1 ml of 0.05M HNO₃ into a 7 ml Savillex vial. The final Sr fraction was dried before analysis on the PCIGR Thermo Finnigan Triton[™] thermal ionization mass spectrometer. The standard reference material NIST® SRM® 987 (National Institute of Standards and Technology, 2007) was used as a Sr standard and was analyzed after every three to four samples. Isotope ratios were normalized internally to 86 Sr/ 88 Sr = 0.11940 using an exponential correction to correct for fractionation. Data are normalized to the average value of NIST SRM987. Uncertainty in ⁸⁷Sr/⁸⁶Sr is expressed as ± 2 standard error of the mean, that is, the internal error. The external error was assessed by duplicate analysis of the same sample.

Sulfur isotopes

Sulfur isotope analyses of 35 samples were performed at the Ján Veizer Stable Isotope Laboratory. Analyses were obtained using pure mineral separates of pyrite, galena, sphalerite, and barite, which were handpicked under a binocular microscope and crushed into a powder using an agate mortar and pestle. Care was taken to ensure that mineral separates were pure; however, fine inclusions of other sulfide phases may be present. Sulfide and sulfate minerals were weighed into tin capsules with at least twice as much WO₃ by mass and loaded into the ISOTOPE Cube autosampler carousel. In the ISOTOPE Cube, each sample falls onto the top of a solid chemical column at 1150°C and is flash combusted at 1800°C with the addition of oxygen. Ultra-pure He is used to carry the resulting gases through the column(s) of oxidizing/reducing chemicals to obtain N₂, CO₂, H₂O, and SO₂. Water is cleaned out of the system by SICAPENT[®]

traps. The SO₂ is separated for analysis by the chemical adsorption ('trap and purge') method and carried by He into the Thermo Finnigan Delta Plus XP IRMS via a Conflo IV interface for analysis. Calibrated internal standards were prepared with every batch of samples for data normalization. The sulfur ratios are reported in δ notation relative to the Vienna–Canyon Diablo Troilite (VCDT) standard with an analytical precision of ± 0.3‰ (2 σ).

Pb isotopes

Lead isotope analyses of 29 samples were conducted by J. Gabites at PCIGR. Clean galena, pyrite, and sphalerite crystals were handpicked and dissolved in 2N hydrochloric acid, dried, then washed with 4N hydrochloric acid and redried. Approximately 10 to 25 mg of the lead in chloride form was loaded on a rhenium filament using a phosphoric acid-silica gel emitter. The isotopic compositions were determined in peak-switching mode using a modified VG54R thermal ionization mass spectrometer. The measured ratios were corrected for instrumental mass fractionation of 0.12%/amu (Faraday collector) or 0.43%/amu (Daly collector) based on repeated measurements of the NIST SRM 981 standard (National Institute of Standards and Technology, 1991) and the values recommended by Thirlwall (2000). Errors, including all mass fractionation and analytical errors, were numerically propagated using the technique of Roddick (1987). All errors are quoted at the 2σ level.

RESULTS

Carbon, oxygen, and strontium isotopes in MVT deposits

Monarch and Kicking Horse MVT deposits

The least-altered dolostone of the middle Cambrian Cathedral Formation at the Monarch-Kicking Horse deposits has $\delta^{18}O_{VPDB}$ values from -15.2 to -14.5% and $\delta^{13}C_{VPDB}$ values from -0.3 to 0‰ (Fig. 10; Table 2). Altered 'replacive dolomite' of the Cathedral Formation at Monarch-Kicking Horse has a large range of $\delta^{18}O_{VPDB}$ values from -19.2 to -13.3% and $\delta^{13}C_{VPDB}$ values from -1.8 to +0.9%, and a ⁸⁷Sr/⁸⁶Sr value of 0.71460 (Fig. 11). The sparry and saddle dolomite associated with the grey and white mineralized breccia has $\delta^{18}O_{VPDB}$ values of -20 to -15.3‰, $\delta^{13}C_{VPDB}$ values of -2.3 to -0.1‰, and ⁸⁷Sr/⁸⁶Sr values from 0.70949 to 0.71176. Vandeginste et al. (2007) reported ⁸⁷Sr/⁸⁶Sr values from 0.7106 to 0.7162 for this dolomite (their 'stage 3' dolomite). Late calcite filling of veins and vugs shows a high range of values, with $\delta^{18}O_{VPDB}$ between -18.8 and -17.3%, $\delta^{13}C_{\text{VPDB}}$ of –0.9‰, and $^{87}Sr/^{86}Sr$ of 0.71002.



Figure 10. Plot of $\delta^{13}C_{VPDB}$ versus $\delta^{18}O_{VPDB}$ for host carbonate rocks, magnesite, altered ('replacive') dolomite, and sparry and saddle dolomite from selected deposits of the southern Canadian Rocky Mountains. Refer to Table 2 for ranges of values. The fields of Cambrian and Devonian marine carbonate values (CMC and DMC, respectively; Veizer et al., 1999) are shown for reference. Also shown are fields for hydrothermal dolomite from Monarch and Kicking Horse deposits (Vandeginste et al., 2007), and Cambrian hydrothermal dolomite from the southern Canadian Rocky Mountains (Nesbitt and Muehlenbachs, 1994; Yao and Demicco, 1997). The generalized trends for burial, hydrothermal, and meteoric fluids of Choquette and James (1987) are illustrated by arrows. All isotope values are reported relative to the Vienna Pee-Dee Belemnite (VPDB) standard.

Shag MVT deposits

Two samples of least-altered host dolostone (middle to upper Cambrian Eldon and Waterfowl formations) from the C-3 and Red Bed showings at the Shag deposit have $\delta^{18}O_{VPDB}$ values of -13.3 and -9.0% and $\delta^{13}C_{VPDB}$ values of +0.8 and +1.2%, respectively. The altered 'replacive dolomite' from the BM, C-4, and Red Bed showings has similar $\delta^{18}O_{VPDB}$ values to the least-altered dolostone with values from -14.2 to -9.8%, and $\delta^{13}C_{VPDB}$ values of -2.3 to +0.2%. The coarse-grained, white sparry dolomite at the BM, C-4, and Red Bed showings has $\delta^{18}O_{VPDB}$ values between -16.5 and -13.5% and $\delta^{13}C_{VPDB}$ values of -1.1 to +0.8%. The $^{87}Sr/^{86}Sr$ value of the sparry dolomite at C-4 is 0.71163. Each showing

produces a distinct cluster in $\delta^{13}C_{VPDB}$ versus $\delta^{18}O_{VPDB}$ space (Fig. 10), and sparry dolomite in all showings has lower $\delta^{18}O_{VPDB}$ values than their host dolostone.

Hawk Creek MVT deposits

The grey, argillaceous dolomitic limestone of the McKay Group, which hosts the Hawk Creek deposit, has $\delta^{18}O_{VPDB}$ values from -11.2 to -9.7% and $\delta^{13}C_{VPDB}$ values from -1.4 to +1.0%. Its ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ value is 0.70964, which is similar to Cambrian marine carbonate rocks. Sparry and saddle dolomite associated with sulfide minerals has $\delta^{18}O_{VPDB}$ values from -13.2 to -11.5%, $\delta^{13}C_{VPDB}$ values from -1.9 to -1.1%, and a ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ value of = 0.71484.

Deposit	Showing	Mineral(s)	Texture	δ¹³C _{VPDB} (‰)	δ ¹⁸ Ο _{VPDB} (‰)	δ ¹⁸ Ο _{SMOW} (‰)	⁸⁷ Sr/ ⁸⁶ Sr
Mount Brussilof	-	Magnesite	Sparry magnesite	–2.9 to –0.7 (av. = –1.4, n = 16)	–19.8 to –15.5 (av. = −17.6, n = 16)	+10.6 to +15.0 (av. = +12.8, n = 16)	0.70866 to 0.70996 (av. = 0.70910, n = 4)
Mount Brussilof	-	Dolomite	Sparry (white and grey)	-1.6 to -0.1 (av. = -1.0, n = 7)	-19.3 to -15.2 (av. = -17.6, n = 7)	+11.0 to +15.2 (av. = +12.8, n = 7)	0.71076 to 0.71469 (av. = 0.71261, n = 4)
Monarch and Kicking Horse	-	Dolomite	Host dolostone	- 0.3 and 0	-15.2 and -14.5	+15.2 and +16.0	-
Monarch and Kicking Horse	-	Dolomite	Altered (replacive) dolomite	-1.8 to +0.9 (av. = -0.4, n = 14)	−19.2 to −13.3 (av. = −16.6, n = 14)	+11.1 to +17.2 (av. = +14.3, n = 14)	0.71460
Monarch and Kicking Horse	-	Dolomite	Sparry and saddle (white)	–2.3 to –0.1 (av. = –1.3, n = 21)	-20.0 to -15.3 (av. = -18.1, n = 21)	+10.3 to +15.2 (av. = +12.3, n = 21)	0.70949 to 0.71176 (av. = 0.71002, n = 5)
Monarch and Kicking Horse	-	Calcite	Veins and vugs	-0.9 (av. = -0.9, n = 3)	-18.8 to -17.3 (av. = -18.3, n = 3)	+11.5 to +13.1 (av. = +12.1, n = 3)	0.71002
Shag	C-3 and Red Bed	Dolomite	Host dolostone (least altered)	+1.2 and +0.8	–13.3 and –9.0	+17.2 and +21.7	-
Shag	BM, C-4, and Red Bed	Dolomite	Altered (replacive) dolomite	-2.3 to +0.2 (av. = -1.3, n = 7)	-14.2 to -9.8 (av. = -11.6, n = 7)	+16.3 to +20.8 (av. = 18.9, n = 7)	-
Shag	BM, C-4, and Red Bed	Dolomite	Sparry dolomite	-1.1 to +0.8 (av. = -0.3, n = 5)	-16.5 to -13.5 (av. = -14.7, n = 5)	+13.8 to +17.0 (av. = +15.7, n = 5)	0.71163
Shag	BM	Dolomite	Altered (replacive) and sparry dolomite	-2.3 to -0.6 (av. = -1.6, n = 7)	-16.5 to -9.8 (av. = -11.9, n = 7)	+13.8 to +20.8 (av. = +18.6, n = 7)	_
Shag	C-4	Dolomite	Altered (replacive) and sparry dolomite	-0.3 to +0.8 (av. = +0.2, n = 3)	−15.1 to −13.9 (av. = −14.5, n = 3)	+15.3 to +16.6 (av. = +15.9, n = 3)	0.71163
Shag	Red Bed	Dolomite	Host dolostone (least altered) and altered (replacive) dolomite	+0.2 and +0.8	–13.3 and –14.2	+16.3 and +17.2	_
Shag	C-3	Dolomite	Host dolostone (least altered) and sparry dolomite	–0.5 and +1.2	–13.9 and –9.0	+16.6 and +21.7	_

 Table 2. Carbon, oxygen, and strontium isotope composition of carbonates from carbonate-hosted deposits of southeastern

 British Columbia.

Table2 (cont.). Carbon, oxygen, and strontium isotope composition of carbonates from carbonate-hosted deposits of southeaster	ern
British Columbia.	

Deposit	Showing	Mineral(s)	Texture	δ ¹³ C _{vpdb} (‰)	δ ¹⁸ Ο _{VPDB} (‰)	δ¹8O _{SMOW} (‰)	⁸⁷ Sr/ ⁸⁶ Sr
Hawk Creek	-	Dolomite	Dolomitic limestone	-1.4 to +1.0 (av. = -0.3, n = 3)	-11.2 to -9.7 (av. = -10.6, n = 3)	+19.3 to +20.9 (av. = +19.9, n = 3)	0.70964
Hawk Creek	-	Dolomite	Sparry and saddle (white)	-1.9 to -1.1 (av. = -1.4, n = 3)	-13.2 to -11.5 (av. = -12.4, n = 3)	+17.3 to +19.0 (av. = +18.1, n = 3)	0.71484
Munroe	-	Dolomite	Host dolostone (least altered)	+0.2 to +0.8 (av. = +0.5, n = 4)	-14.4 to -13.9 (av. = -14.2, n = 4)	+16.1 to +16.6 (av. = +16.3, n = 4)	_
Boivin	-	Dolomite	Host dolostone (least altered)	+0.8 and +0.6	-12.2 and -12.0	+18.3 to +18.5	_
Munroe	-	Dolomite	Saccharoidal dolomite	+0.3 to +0.7 (av. = +0.5, n = 3)	-14.8 to -13.8 (av. = -14.1, n = 3)	+15.7 to +16.7 (av. = +16.4, n = 3)	_
Munroe	_	Dolomite	Sparry and saddle (white)	-5.6 to +0.4 (av. = -1.7, n = 8)	-16.4 to -13.4 (av. = -14.5, n = 8)	+13.9 to +17.1 (av. = +15.9, n = 8)	0.71009
Boivin	_	Dolomite	Sparry and saddle (white)	-8.6 to +1.1 (av. = -3.1, n = 8)	-13.6 to -12.1 (av. = -12.8, n = 8)	+16.8 to +18.4 (av. = +17.7, n = 8)	-
Munroe	_	Calcite	Late calcite vein	-2.2	-22.5	7.7	_
Munroe	_	Dolomite	Late dolomite vein	-0.3	-19.7	10.7	_
Oldman	_	Dolomite	Host dolomitic limestone	-0.1 to +0.6 (av. = 0.3, n = 4)	-12.0 to -9.2 (av. = -10.4, n = 4)	+18.5 to +21.4 (av. = +20.2, n = 4)	0.71034 to 0.71044 (av. = 0.71038, n = 3)
Oldman	_	Calcite	Calcite, coarse- grained, white	-2.2 and -2.9	-11.6 and -11.7	+18.8 and +18.9	_
Rock Canyon Creek	_	Dolomite	Host dolomitic limestone (least altered, unmineralized)	-2.9 to +1.2 (av. = -0.6, n = 6)	–10.3 to –7.1 (av. = –8.7, n = 6)	+20.3 to +23.5 av. = +21.9, n = 6)	0.70866 to 0.70903 (av. = 0.70891, n = 3)
Rock Canyon Creek	-	Dolomite	Altered dolostone (with fluorite)	-2.8 and -3.5	-13.1 and -12.2	+17.4 and +18.3	0.70823
Rock Canyon Creek	-	Dolomite	REE–F-Ba dolomite	-2.4 to -0.6 (av. = -1.7, n = 4)	-18.8 to -14.7 (av. = -17.2, n = 4)	+11.5 to +15.7 (av. = +13.1, n = 4)	0.70588 and 0.70873
Rock Canyon Creek	_	Dolomite	Saddle dolomite	-3.8	-16.1	14.3	_
Rock Canyon Creek		Calcite	Late calcite breccia-matrix and veins	-5.2 to -0.3 (av. = -3.7, n = 4)	-18.2 to -15.1 (av. = -16.5, n = 4)	+12.1 to +15.3 (av. = +13.8, n = 4)	0.70922 and 0.70930

Abbreviations: REE: rare-earth element; SMOW: Vienna Standard Mean Ocean Water; VPDB: Vienna Pee-Dee Belemni standard



Figure 11. Plot of $\delta^{18}O_{VPDB}$ versus ${}^{87}Sr/{}^{86}Sr$ for various carbonate rocks associated with deposits of the southern Canadian Rocky Mountains. Middle Cambrian and Devonian marine carbonate values are from Veizer et al. (1999). The maximum strontium isotope ratio of basinal shale (MASIRBAS) is from Machel and Cavell (1999).

Munroe and Boivin MVT deposits

The least-altered host dolostone (Late Devonian Palliser Formation) at Munroe-Boivin has $\delta^{18}O_{VPDB}$ values from -14.4 to -12.0% and $\delta^{13}C_{VPDB}$ values from +0.2 to +0.8%. White to light grey saccharoidal dolomite has $\delta^{18}O_{VPDB}$ values from -14.8 to -13.8% and $\delta^{13}C_{VPDB}$ values from +0.3 to +0.7%. White, coarse to very coarse sparry and saddle dolomite has $\delta^{18}O_{VPDB}$ values from -16.4 to -12.1%, $\delta^{13}C_{VPDB}$ values from -8.6 to +1.1%, and an $^{87}Sr/^{86}Sr$ value of 0.71009.

Oldman MVT deposits

At Oldman, the host dolostone (Late Devonian Palliser Formation) has $\delta^{18}O_{VPDB}$ values from -12.0 to -9.2‰ and $\delta^{13}C_{VPDB}$ values from -0.1 to +0.6‰; ⁸⁷Sr/⁸⁶Sr values range from 0.71034 to 0.71044. Two samples from the mineralized calcite have $\delta^{18}O_{VPDB}$ values of -11.6 and -11.7‰ and $\delta^{13}C_{VPDB}$ values of -2.9 and -2.2‰, respectively.

Carbon, oxygen, and strontium isotopes in the Mount Brussilof magnesite deposit

Magnesite at Mount Brussilof has $\delta^{18}O_{VPDB}$ values from -19.8 to -15.5% and $\delta^{13}C_{VPDB}$ values from -2.9 to -0.7% (Fig. 10; Table 2). The ${}^{87}\text{Sr}{}^{86}\text{Sr}$ values range from 0.70866 to 0.70996, similar to middle Cambrian marine carbonate rocks (Fig. 11). The sparry dolomite, which crosscuts the magnesite, has $\delta^{18}O_{VPDB}$ values from -19.3 to -15.2% and $\delta^{13}C_{VPDB}$ values from -1.6 to -0.1%. The ${}^{87}\text{Sr}{}^{86}\text{Sr}$ values for sparry dolomite range from 0.71076 to 0.71469 (Fig. 11).

Carbon, oxygen, and strontium isotopes in the Rock Canyon Creek REE-F-Ba deposit

The dark grey dolomitic limestone (least altered, unmineralized host rock) of the Middle Devonian Cedared and Burnais formations has $\delta^{13}C_{VPDB}$ values from -2.9 to +1.2‰ and $\delta^{18}O_{VPDB}$ values from -10.3 to -7.1‰ (green squares in Fig. 12; Table 2). Its ⁸⁷Sr/⁸⁶Sr values range from 0.70866 to



Figure 12. Plot of $\delta^{13}C_{VPDB}$ versus $\delta^{18}O_{VPDB}$ for carbonate phases at the Rock Canyon Creek REE-F-Ba deposit. Fields from Zhu (2000) are shown for comparison; other fields are the same as those in Figure 10. All isotope values are reported relative to the Vienna Pee-Dee Belemnite (VPDB) standard.

0.70903. Zhu (2000) obtained similar values for Devonian limestone: -1.4 to +1.0% $\delta^{13}C_{VPDB}$, -9.4 to -8.1 % $\delta^{18}O_{VPDB}$, and 0.70862 $^{87}Sr/^{86}Sr$.

Two altered dolostone samples with fluorite have $\delta^{13}C_{VPDB}$ values of -2.8 and -3.5‰ and $\delta^{18}O_{VPDB}$ values of -13.1 and -12.2‰ (yellow diamonds in Fig. 12), respectively, and an ⁸⁷Sr/⁸⁶Sr value of 0.70823 (Fig. 11). This dolostone, which has weathered to light grey to pale brown, has a mottled texture and is crosscut by numerous fluorite veinlets and fluorite-filled vugs. It is equivalent to the 'replacive dolomite' associated with MVT deposits and may correspond to the mineralized ferroan dolomite of Zhu (2000), which has $\delta^{13}C_{VPDB}$, $\delta^{18}O_{VPDB}$, and $^{87}Sr/^{86}Sr$ values of -2.6 to -0.3‰, -18.8 to -13.0‰, and 0.70336 to 0.70462, respectively.

One sample of saddle dolomite associated with fluorite veinlets and vugs has a $\delta^{13}C_{VPDB}$ value of -3.8% and a $\delta^{18}O_{VPDB}$ value of -16.1% (white circle in Fig. 12). Saddle dolomite associated with fluorite-REE mineralization analyzed by Zhu (2000) has $\delta^{13}C_{VPDB}$ values from -1.1 to -1.9%and $\delta^{18}O_{VPDB}$ values from -13 to -18.9%. Zhu (2000) reports a $^{87}Sr/^{86}Sr$ value of 0.70784 for this saddle dolomite. Dolomite associated with REE-F-Ba mineralization has $\delta^{18}O_{VPDB}$ from -18.8 to -14.7‰, $\delta^{13}C_{VPDB}$ from -2.4 to -0.6‰ (red triangles in Fig. 12), and ⁸⁷Sr/⁸⁶Sr from 0.70588 to 0.70873 (Fig. 11). Our $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values plot in the field of syn-mineralization ferroan dolomite of Zhu (2000); however, our ⁸⁷Sr/⁸⁶Sr values are higher than those reported by Zhu (2000) for ferroan dolomite associated with mineralization (0.70336 and 0.70462). Values of ⁸⁷Sr/⁸⁶Sr from 0.703753 to 0.709755 (av. 0.70611, n = 15) were obtained for a section of altered dolomitic limestone rich in REE (Araoka et al., 2018).

Calcite vein and breccia matrix cement associated with fluorite have $\delta^{13}C_{VPDB}$ values from -0.3 to -5.2‰, $\delta^{18}O_{VPDB}$ values from -15.1 to -18.2‰, and ${}^{87}Sr/{}^{86}Sr$ values from 0.7092 to 0.7093 (blue circles in Fig. 12). Zhu (2000) reported ${}^{87}Sr/{}^{86}Sr$ values of 0.70822 to 0.70998.

Sulfur isotopes

Samples of galena, sphalerite, pyrite, and barite from the MVT, magnesite, and REE-F-Ba deposits were analyzed for their sulfur isotope composition (Table 3). The sulfide minerals within the southern Rocky Mountain foreland belt have

Table 3. S	ulfur isot	ope co	mposition	of sulfide	minerals	and bari	e from	carbonate-hosted	deposits of	southeastern	British
Columbia.											

Sample no.	Deposit	Host rocks	Mineral(s)	Texture(s)	δ ³⁴ S _{vcdt} of pyrite (‰)	δ ³⁴ S _{VCDT} of galena (‰)	δ ³⁴ S _{VCDT} of sphalerite (‰)	δ ³⁴ S _{VCDT} of barite (‰)	References
WH-2f	Oldman River	Dolostone, Upper Devonian Palliser Formation	Galena	Galena forming veins and veinlets	_	10.8	_	_	Paradis et al. (2006b)
WH-2d	Oldman River	Dolostone, Upper Devonian Palliser Formation	Galena	Galena forming veins and veinlets	-	9.9	-	-	Paradis et al. (2006b)
WH-2D	Oldman River	Dolostone, Upper Devonian Palliser Formation	Galena	Galena forming veins and veinlets	_	11.1	_	_	This study
WH-2F	Oldman River	Dolostone, Upper Devonian Palliser Formation	Galena	Galena forming veins and veinlets	_	12.3	_	-	This study
Min Id: 82J-M- 42	Oldman River	Dolostone, Upper Devonian Palliser Formation	Galena, sphalerite, pyrite	No information available	15.9	9.9	15.6	-	Holter (1973, 1977)
Hawk Ck 8	Hawk Creek	Dolomitic limestone, upper Cambrian– Ordovician McKay Group	Sphalerite	Coarse- grained, honey-coloured sphalerite in vein or cavity that is filled by calcite	_	_	28.8	_	This study
1	Hawk Creek	Dolomitic limestone, upper Cambrian– Ordovician McKay Group	Galena, sphalerite, pyrite	No information available	27.9	24.8	25.9	_	Evans et al. (1968)
2	Hawk Creek	Dolomitic limestone, upper Cambrian– Ordovician McKay Group	Sphalerite, pyrite	No information available	25.6	_	24.9	_	Evans et al. (1968)
3	Hawk Creek	Dolomitic limestone, upper Cambrian– Ordovician McKay Group	Sphalerite, pyrite	No information available	27.9	_	25.1	_	Evans et al. (1968)

Sample no.	Deposit	Host rocks	Mineral(s)	Texture(s)	δ ³⁴ S _{VCDT} of pyrite (‰)	δ ³⁴ S _{VCDT} of galena (‰)	δ ³⁴ S _{vcDT} of sphalerite (‰)	δ ³⁴ S _{VCDT} of barite (‰)	References
4	Kicking Horse	Dolostone, middle Cambrian Cathedral Formation	Sphalerite	Dark iron-rich sphalerite	_	_	31.3	_	Evans et al. (1968)
4	Kicking Horse	Dolostone, middle Cambrian Cathedral Formation	Galena, sphalerite	Pale yellow, less iron rich than sphalerite (above); coexisting with galena	_	25.8	29.6	_	Evans et al. (1968)
5	Kicking Horse	Dolostone, middle Cambrian Cathedral Formation	Sphalerite	No information available	_	_	20.1	_	Evans et al. (1968)
Kick 16-3	Kicking Horse	Dolostone, middle Cambrian Cathedral Formation	Sphalerite	Medium- grained yellow sphalerite surrounded by galena in sparry dolomite and calcite (stockwork)	_	_	32	_	This study
Kick 16-8	Kicking Horse	Dolostone, middle Cambrian Cathedral Formation	Sphalerite	Fine-grained honey-coloured sphalerite replacing dolostone	_	_	33.4	_	This study
Kick 16-11	Kicking Horse	Dolostone, middle Cambrian Cathedral Formation	Sphalerite	Coarse- grained yellow sphalerite surrounded by sparry dolomite and calcite (stockwork)	_	_	33.8	_	This study
6	Monarch	Dolostone, middle Cambrian Cathedral Formation	Galena, sphalerite	No information available	_	21.8	23.4	-	Evans et al. (1968)
7	Monarch	Dolostone, middle Cambrian Cathedral Formation	Galena, sphalerite	No information available	_	17.6	19.1	-	Evans et al. (1968)

 Table 3 (cont.).
 Sulfur isotope composition of sulfide minerals and barite from carbonate-hosted deposits of southeastern

 British Columbia.

Sample no.	Deposit	Host rocks	Mineral(s)	Texture(s)	δ ³⁴ S _{vcdt} of pyrite (‰)	δ ³⁴ S _{VCDT} of galena (‰)	δ ³⁴ S _{VCDT} of sphalerite (‰)	δ ³⁴ S _{VCDT} of barite (‰)	References
Mon 16-8	Monarch	Dolostone, middle Cambrian Cathedral Formation	Pyrite	Pyritohedrons (slightly oxidized on edges)	30.7	_	-	_	This study
Mon 16- 15-1	Monarch	Dolostone, middle Cambrian Cathedral Formation	Pyrite	Large patch of fine-grained pyrite replacing dolostone (slightly oxidized on edges)	30	_	_	_	This study
Mon 16- 15-2	Monarch	Dolostone, middle Cambrian Cathedral Formation	Pyrite	Large patch of fine-grained pyrite replacing dolostone (slightly oxidized on edges)	30.1	_	-	_	This study
Mon 16- 10-1	Monarch	Dolostone, middle Cambrian Cathedral Formation	Pyrite	Fine-grained pyrite forming large chunks and veinlets cutting carbonates	31.8	_	_	_	This study
Mon 16- 10-2	Monarch	Dolostone, middle Cambrian Cathedral Formation	Pyrite	Fine-grained pyrite forming large chunks and veinlets cutting carbonates	32.2	_	-	_	This study
Mon 16-14	Monarch	Dolostone, middle Cambrian Cathedral Formation	Pyrite	Anhedral to subhedral pyrite forming patches in carbonates	30.6	_	-	_	This study
Mon 16-1	Monarch	Dolostone, middle Cambrian Cathedral Formation	Pyrite	Small pyritohedrons	31	-	-	_	This study
Mon 16-5	Monarch	Dolostone, middle Cambrian Cathedral Formation	Galena	Coarse-grained galena forming aggregates cutting dolomite	_	30.1	-	_	This study

 Table 3 (cont.).
 Sulfur isotope composition of sulfide minerals and barite from carbonate-hosted deposits of southeastern

 British Columbia.

Table 3 (cont.). Sulfur isotope composition of sulfide minerals and barite from carbonate-hosted deposits of south	eastern
British Columbia.	

Sample no.	Deposit	Host rocks	Mineral(s)	Texture(s)	δ ³⁴ S _{vcDT} of pyrite (‰)	δ ³⁴ S _{VCDT} of galena (‰)	δ ³⁴ S _{VCDT} of sphalerite (‰)	δ ³⁴ S _{VCDT} of barite (‰)	References
Mon 16- 11-1	Monarch	Dolostone, middle Cambrian Cathedral Formation	Pyrite	Massive aggregate of fine-grained pyrite forming aggregates in carbonates	29.4	_	-	-	This study
Mon 16-13	Monarch	Dolostone, middle Cambrian Cathedral Formation	Galena	Coarse-grained galena forming aggregates and veinlets in massive sphalerite	_	26.8	_	_	This study
Shag C4-7	Shag (showing C4)	Dolostone, middle Cambrian Waterfowl Formation	Galena	Coarse- grained galena replacing carbonates	_	15.5	-	_	This study
Shag 5X	Shag (showing Red Bed)	Dolostone, middle Cambrian Waterfowl Formation	Galena	Coarse- grained galena replacing carbonates	_	19.2	-	_	This study
Munroe 16-5 ga	Munroe	Dolostone, Upper Devonian Palliser Formation	Galena	Coarse- grained galena in cavity filled by sparry and saddle dolomite and coarse-grained sphalerite	_	28.8	_	_	This study
Munroe 16-5 sph	Munroe	Dolostone, Upper Devonian Palliser Formation	Sphalerite	Coarse-grained sphalerite (amber colour) in vug filled by sparry and saddle dolomite	_	_	36.3	_	This study
Munroe 16-5-4	Munroe	Dolostone, Upper Devonian Palliser Formation	Galena	Coarse- grained galena crystal in cavity or vein; associated with amber- coloured sphalerite	_	32.5	_	_	This study
Munroe 16-5-3	Munroe	Dolostone, Upper Devonian Palliser Formation	Sphalerite	Coarse-grained sphalerite (amber colour) in cavity or vein; associated with galena	_	_	35.3	_	This study

Table 3 (cont.). Sulfur isotope composition of sulfide minerals and barite from carbonate-hosted deposits of southeastern	
British Columbia.	

Sample no.	Deposit	Host rocks	Mineral(s)	Texture(s)	δ ³⁴ S _{VCDT} of pyrite (‰)	δ ³⁴ S _{VCDT} of galena (‰)	δ ³⁴ S _{vcDT} of sphalerite (‰)	δ ³⁴ S _{VCDT} of barite (‰)	References
Munroe 16-5-1	Munroe	Dolostone, Upper Devonian Palliser Formation	Sphalerite	Coarse-grained sphalerite (amber colour) in vug-cavity filled by sparry and saddle dolomite	_	_	36.7	-	This study
Munroe 16-5-2	Munroe	Dolostone, Upper Devonian Palliser Formation	Sphalerite	Coarse-grained sphalerite (amber colour) in vug-cavity filled by sparry and saddle dolomite	_	_	36.6	-	This study
Boivin 3-2	Boivin	Dolostone, Upper Devonian Palliser Formation	Sphalerite	Coarse-grained, pale-yellow sphalerite replacing dolostone	_	_	-2.3	_	This study
Boivin 3-2	Boivin	Dolostone, Upper Devonian Palliser Formation	Sphalerite	Coarse-grained, pale-yellow sphalerite replacing dolostone	-	_	-2.8	_	This study
MB-16-11	Mount Brussilof	Magnesite, middle Cambrian Cathedral Formation	Pyrite	Pyritohedrons	31.7	-	_	_	This study
MB-16- 07-1	Mount Brussilof	Magnesite, middle Cambrian Cathedral Formation	Pyrite	Subhedral to euhedral grains of pyrite	30.3	-	_	_	This study
MB-16- 07-2	Mount Brussilof	Magnesite, middle Cambrian Cathedral Formation	Pyrite	Subhedral to euhedral grains of pyrite	29.4	-	_	_	This study
MB-2018- 1	Mount Brussilof	Magnesite, middle Cambrian Cathedral Formation	Pyrite	Pyritohedrons	Pyritohedrons 32.9		_	-	This study
MB 16-12	Mount Brussilof	Magnesite, middle Cambrian Cathedral Formation	Pyrite	Pyrite veins and fractures sealed by carbonate in magnesite; pre-dating later deformation	23.6				This study
MB 16-8	Mount Brussilof	Magnesite, middle Cambrian Cathedral Formation	Pyrite	Fine-grained pyrite forming veinlets and stringers in magnesite	20.5				This study
RC-01- 38.7	Rock Canyon Creek	Dolostone, Middle Devonian Cedared and Burnais formations	Barite	Tabular crystals in dolostone				31.7	This study

a large range of $\delta^{34}S_{VCDT}$ values (-2.3 to +36.6%; Fig. 13). Two sphalerite analyses from the Boivin deposit have the lowest $\delta^{34}S_{VCDT}$ values (-2.3 and -2.8%); all other $\delta^{34}S_{VCDT}$ values within the southern Rocky Mountain foreland belt are positive, from +9.9 to +36.6%. The $\delta^{34}S_{VCDT}$ values of sulfide minerals at Oldman (pyrite = +15.9%); galena = +9.9 to +12.3% [av. = +10.8%, n = 5]; sphalerite = +15.6%) are generally lower than values obtained from the other MVT deposits of the southern Rocky Mountains (except two very low values at Boivin). Within some deposits (e.g. Hawk Creek, Oldman, Shag), the variation in the $\delta^{34}S_{VCDT}$ values of sulfide minerals is small (i.e. $\Delta_{sulfide} < 6\%$), whereas in other deposits, the variation is large (e.g. Mount Brussilof $\Delta_{sulfide}$ = 12.4‰).

Values of $\delta^{34}S_{VCDT}$ for pyrite within the MVT deposits range from +25.6 to +32.2‰ (av. = +29.7‰, n = 11), except for Oldman (+15.9‰). This range of values is similar to pyrite at Mount Brussilof, which has values from +20.5 to +32.9‰ (av. = +28.1‰, n = 6). Pyrite at Mount Brussilof with the lowest $\delta^{34}S_{VCDT}$ values (+20.5 and +23.6‰) is from the network of veins crosscutting magnesite; the higher values (+31.8 and +32.9‰) are from pyritohedrons. Pyritohedrons at Monarch ($\delta^{34}S_{VCDT}$ = +30.7 and +31.0‰) have similar values. Sphalerite in MVT deposits has a range of positive $\delta^{34}S_{VCDT}$ values (+19.1 to +36.7%; av. = +29.5%, n = 16), except for two negative values (-2.2 and -2.8%) from Boivin. Galena ranges from +9.9 to +32.5% (av. = +19.8, n = 15; including Oldman).

One barite sample from Rock Canyon Creek (RC-01-38.7) was analyzed and produced a $\delta^{34}S_{VCDT}$ value of +31.7‰. Barite from Ba-Pb-Zn veins in the Rocky Mountains have a wide range of $\delta^{34}S_{VCDT}$ values (+17.8 to +32.3‰; av. = +25.6‰, n = 19; S. Paradis, unpub. data, 2020). Anhydrite from the Upper Devonian Leduc and Nisku formations in the Western Canada Sedimentary Basin has similar values (+20.6 to +31.7‰; av. = +29.2‰, n = 11; Davies and Wendte, 2005).

Lead isotopes

Lead isotope data (Table 4) are plotted on conventional covariation diagrams (Fig. 14a, b). Analyses of ²⁰⁴Pb for some sphalerite and pyrite did not give credible results and these data are omitted on the ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb diagram (Fig. 14a).



Figure 13. Sulfur isotope values of carbonate-hosted deposits of the southern Canadian Rocky Mountains. Data from other Mississippi Valley–type (MVT) deposits in Alberta (Baker Creek, Beaver River, and Eldon) are from Evans et al. (1968) and the range of values for anhydrite from the Upper Devonian Leduc and Nisku formations (Davies and Wendte, 2005) are plotted for reference; all other data are from this study (see Table 3 for range of values).

Sample no.	Deposit	Showing/ orebody	Mineral(s)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁸ Pb/ ²⁰⁶ Pb	References
Cluster 1									
Mon 16-3	Monarch	-	Galena	18.371	15.588	38.605	0.849	2.102	This study
Mon 16-5	Monarch	-	Galena	18.518	15.604	38.615	0.843	2.085	This study
MON-16-5x	Monarch	-	Galena	18.425	15.657	38.649	0.850	2.098	This study
Monarch-1	Monarch	_	Galena	18.201	15.623	38.887	0.858	2.137	This study
Kick 16-3	Kicking Horse	-	Galena	18.385	15.632	38.485	0.850	2.093	This study
Kick 16-9	Kicking Horse	-	Galena	18.43	15.675	38.674	0.851	2.098	This study
30715-001#	Monarch	-	Galena	18.557	15.629	38.756	0.842	2.089	Godwin et al. (1988)
30716-001#	Kicking Horse	_	Galena	18.558	15.697	38.857	0.846	2.094	Godwin et al. (1988)
MUN-16-5x	Munroe	_	Galena	18.591	15.661	38.763	0.842	2.085	This study
MUN16-3a	Munroe	_	Sphalerite	19.349	15.583	39.358	0.805	2.034	This study
Boivin	Boivin	_	Sphalerite	18.24	15.597	37.282	0.855	2.044	This study
Boivin	Boivin	_	Sphalerite	19.313	16.716	40.172	0.866	2.080	This study
Boivin 1	Boivin	_	Sphalerite	18.345	15.401	37.535	0.840	2.046	This study
Boivin 3-2	Boivin	_	Sphalerite	_	_	30.226	0.908	2.018	This study
Boivin 3-2	Boivin	-	Sphalerite	17.604	15.825	35.468	0.899	2.015	This study
Cluster 2		1		1	1	1	I	1	l
Shag C4-7	Shag	C-4	Galena	19.195	15.732	39.625	0.820	2.064	This study
Shag 5 x	Shag	Red Bed	Galena	19.208	15.782	39.657	0.822	2.065	This study
Shag C-4, 3	Shag	C-4	Galena	19.288	15.765	39.859	0.817	2.067	This study
Shag C-4, 7	Shag	C-4	Galena	19.19	15.759	39.733	0.821	2.071	This study
Shag R98:16	Shag	Shag, Red Bed	Galena	19.235	15.814	39.823	n.d.	n.d.	Graf (1999)
30407-001	Shag	Shag (Red Bed)	Galena	19.078	15.696	39.241	0.823	2.057	Godwin et al. (1988)
30407-002	Shag	Shag (C-4)	Galena	19.248	15.757	39.718	0.819	2.064	Godwin et al. (1988)
30407-003	Shag	Shag (PAD)	Galena	19.213	15.758	39.6	0.820	2.061	Godwin et al. (1988)
30407-004	Shag	Shag (PAD)	Galena	19.148	15.714	39.447	0.821	2.060	Godwin et al. (1988)
Cluster 3									
MUN16-1b	Munroe	_	Sphalerite	19.926	15.813	40.52	0.794	2.034	This study
MB-16-12	Mount Brussilof	_	Pyrite	19.486	15.8	39.292	0.811	2.016	This study
MB 2018 1-3	Mount Brussilof	_	Pyrite	19.512	15.472	38.395	0.793	1.968	This study
Hawk Ck 7	Hawk Creek	_	Galena	19.404	15.797	39.357	0.814	2.028	This study
Hawk Ck 8	Hawk Creek	_	Galena	19.397	15.771	39.342	0.813	2.028	This study
Hawk Creek 8	Hawk Creek	_	Galena	19.49	15.839	39.524	0.813	2.028	This study
Hawk Creek 1	Hawk Creek	_	Sphalerite	18.913	15.434	38.402	0.816	2.030	This study
Hawk Creek 3	Hawk Creek	_	Galena	19.408	15.801	39.681	0.814	2.045	This study
WH-2D	Oldman	-	Galena	21.784	15.96	44.451	0.733	2.041	This study
WH-2F	Oldman	-	Galena	21.788	15.949	44.431	0.732	2.039	This study
WH-2D-gn	Oldman	-	Galena	21.779	15.941	44.44	0.732	2.041	Paradis et al. (2006b)
WH-2F-gn	Oldman	-	Galena	21.778	15.945	44.454	0.732	2.041	Paradis et al. (2006b)

Table 4. Lead isotope composition of sulfide minerals from carbonate-hosted deposits of southeastern British Columbia.

Abbreviations: n.d.: not determined



Figure 14. Lead isotope analyses of mineralization from carbonate-hosted deposits of the southern Rocky Mountains compared to the Cordilleran carbonate trend, which includes Zn-Pb occurrences and deposits of the northern Rocky Mountains, the Mackenzie Mountains, and the Western Canada Sedimentary Basin. The labelled clusters of data are discussed in the text. Both plots include new data from this study (see Table 4 for range of values) and data from Godwin et al. (1988), Graf (1999), and Paradis et al. (2006b). The results are compared to the average mantle, orogene, and upper crust growth curves of Zartman and Doe (1981) and to the shale curve of Godwin and Sinclair (1982): a) plot of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ for galena, pyrite, and sphalerite. The dashed trendline (R² = 0.97) for all the data within the Cordilleran carbonate trend (cluster 3) intersects clusters 1 (samples from Monarch, Kicking Horse and Munroe deposits) and 2 (samples from Shag deposit), and a cluster of unradiogenic lead data from the Lead Mountain Pb-Zn deposit, a vein- and fracture-controlled, carbonate-hosted sulfide-barite deposit located in the western Rocky Mountain foreland belt

Sulfide minerals from carbonate-hosted deposits form three clusters on the ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁷Pb/²⁰⁶Pb versus ²⁰⁸Pb/²⁰⁶Pb diagrams (Fig. 14a, b). Cluster 1 includes data from the least radiogenic samples, forming a tight grouping between the orogene and upper crust curves on the ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb diagram and plotting close to the shale curve on the ²⁰⁷Pb/²⁰⁶Pb versus ²⁰⁸Pb/²⁰⁶Pb diagram. Galena from these samples has ²⁰⁶Pb/²⁰⁴Pb from 18.20 to 18.59, ²⁰⁷Pb/²⁰⁴Pb from 15.59 to 15.697, ²⁰⁷Pb/²⁰⁶Pb from 0.8424 to 0.8584, and ²⁰⁸Pb/²⁰⁶Pb from 2.0851 to 2.1366. This cluster includes samples of the Monarch, Kicking Horse, and Munroe deposits.

Cluster 2 exclusively comprises data from the Shag deposit, with values forming an elongated trend above the upper crust and shale curves and intersecting the latter between 250 and 210 Ma on the ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb diagram (Fig. 14a). Galena from these samples has ²⁰⁶Pb/²⁰⁴Pb from 19.078 to 19.288 and ²⁰⁷Pb/²⁰⁴Pb from 15.696 to 15.814. On the ²⁰⁷Pb/²⁰⁶Pb versus ²⁰⁸Pb/²⁰⁶Pb diagram, these samples form a tight cluster close to the shale curve.

Cluster 3 includes the most radiogenic values and plots in the Cordilleran carbonate trend, defined by Nelson et al. (2002), on ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁷Pb/²⁰⁶Pb versus ²⁰⁸Pb/²⁰⁶Pb diagrams (Fig. 14a, b). This broad cluster includes data from the Pb-Zn occurrences of the northern



Figure 14.(cont.) b) plot of ²⁰⁷Pb/²⁰⁶Pb versus ²⁰⁸Pb/²⁰⁶Pb for sulfide minerals. The dashed trendline (R² = 0.8961) for all the data within the Cordilleran carbonate trend (cluster 3) intersects clusters 1 and 2, and a cluster of unradiogenic lead data from the Lead Mountain Pb-Zn deposit. Abbreviations: MVT: Mississippi Valley–type; Camb: Cambrian; Ord: Ordovician; WCSB: Western Canada Sedimentary Basin.

Rocky Mountains, the Mackenzie Mountains, and the Western Canada Sedimentary Basin. It also includes galena from Oldman and Hawk Creek, pyrite from Mount Brussilof, and sphalerite from the Munroe deposit.

We observed no correlation between the ages of the host rocks and the Pb isotope signatures of the deposits. We cannot verify if there is a correlation between the age of mineralization and the Pb isotope signature because we do not know the exact age of the mineralization of individual deposits.

DISCUSSION AND SYNTHESIS

Constraints from mineral paragenesis

Mineralization within the MVT deposits of the southern Rocky Mountains (Monarch, Kicking Horse, Shag, Munroe, Boivin, and Hawk Creek) shows replacive and openspace–filling textures with similar mineralogy and mineral parageneses. Sulfide minerals (sphalerite, galena, and pyrite) are commonly enclosed in a gangue of dolomite, calcite, and quartz. The mineral parageneses vary from simple (e.g. Boivin, Munroe) to complex (e.g. Monarch, Kicking Horse). Collectively, these deposits have characteristics of MVT deposits and associated breccia vein systems (Leach and Sangster, 1993; Paradis et al., 2007).

We present below a generalized summary description of host rock, mineralogy, and paragenesis, based on samples collected during this study:

1. Mississippi Valley-type deposits are typically hosted in dolostone; the same applies for Mount Brussilof and Rock Canyon Creek (*see* below). During the Paleozoic, the dolostone host (preceded) sulfide mineralization and had a regional distribution along the platform margin, where it replaced a precursor limestone. The dolostone preserves primary fabrics, remnant allochems, and locally possible organic material inclusions and/or insoluble residue. It consists of fine crystalline dolomite with typically nonplanar crystals. The Hawk Creek deposit is an exception to this — there the first phase of sphalerite mineralization replaced limestone and not dolostone.

- 2. Several consecutive phases of dolomite precipitation, including replacement and cementation, are observed throughout the paragenetic sequence. At least one of these phases is associated with sulfide mineralization, except at the Oldman deposit, where only dolomitization of the limestone precursor (i.e. pre-mineralization) took place and sulfide minerals are associated with calcite. In general, Zn-Pb mineralization in the southern Rocky Mountains overlaps with the formation of fine- to medium-grained replacive dolomite and coarser dolomites (saccharoidal and sparry-saddle).
 - a) The host dolostone is replaced by a fabric-destroying, light grey, fine- to medium-grained crystalline dolomite identified here as replacive dolomite. The dolomite crystals exhibit non-planar to planar-s textures and occur in a closely packed mosaic of crystals with diameters of 0.1 to 1 mm. This dolomite forms heterogeneous textures such as mottled or pseudobreccia.
 - b) Dolomite is also found in a crystalline, granular texture, locally called saccharoidal dolomite. It is light grey to white, medium to coarse crystalline (0.2–2.2 mm in diameter), with planar-e to planar-s crystals associated with sphalerite at Munroe and Boivin. The timing of this dolomite phase relative to the replacive dolomite described above is unknown.
 - c) The most recent dolomite phase (except for late dolomite veins/veinlets) is distinguished by coarse (up to 2 mm in diameter), crystalline, white sparry and saddle dolomites filling open spaces (i.e. pore spaces, fractures, vugs, and veinlets) during or after the main phase of sulfide mineralization. These sparry and saddle dolomites are spatially associated with sulfide mineralization at most MVT deposits, as well as magnesite (e.g. Mount Brussilof) and REE-F-Ba mineralization (e.g. Rock Canyon Creek). In some deposits, they are mostly syn-mineralization (e.g. Monarch and Kicking Horse, Rock Canyon Creek, Hawk Creek); in others they are mostly postmineralization and fill fractures and vugs (e.g. Shag, Munroe, Boivin, Mount Brussilof). At rare deposits (e.g. Oldman), sparry and saddle dolomites are not observed; rather, coarse-grained white calcite cement $(\pm$ traces of dolomite) fills the cavities and fractures. The spatial association and coexistence of sparry and saddle dolomites with MVT Zn-Pb mineralization is used as an exploration guide and as evidence for interaction of high-temperature hydrothermal fluids with the host rocks (e.g. Warren, 2000; Davies and Smith, 2006).

- 3. Sulfide minerals consist of sphalerite, galena, and pyrite in a gangue of dolomite and calcite. Quartz is associated with sphalerite at the Shag deposit and, except for rare quartz at Kicking Horse, is mostly absent elsewhere. Barite, chalcopyrite, and native silver were also reported at Monarch and Kicking Horse by Goranson (1937) but were not observed in our samples. Barite is present at Rock Canyon Creek (*see* below).
 - a) Generally, at least three phases of sphalerite are observed: 1) an early phase of finer grained anhedral and intergranular sphalerite disseminated within the dolostone groundmass; this sphalerite replaces the host carbonate rocks (e.g. Fig. 3b, 4d); 2) a later, coarser phase with variable textures forming massive aggregates of anhedral grains with locally colloform bands to void-filling, well-developed colloform textures (e.g. Fig. 4b, 5b, 7c); and 3) the latest phase — large sphalerite grains (up to a few millimetres in diameter) included in vugs and fractures, where they commonly exhibit crustiform banding with colloform textures and colour zonation (e.g. Fig. 3c, 7d). The colours of sphalerite (in hand samples) vary from pale yellow to dark reddish brown. Typically, in the deposits studied, the latest coarser grained sphalerite is pale yellow to amber and the earliest sphalerite contains darker colours. The timing between the sphalerite phases may correspond to different pulses of mineralizing fluids or to a single protracted mineralizing event. Typically, the highest fluid-rock ratio would result in the highest grade of Zn-Pb mineralization (see Kontak et al., this volume).
 - b) Pyrite occurs intermittently in the paragenetic sequence: first as very fine subhedral to euhedral grains disseminated in dolostone (pre-mineralization), second as coarser grains and aggregates associated with sphalerite (syn-mineralization), and third as coarse-grained pyritohedrons present in the sparry dolomite (post-mineralization).
 - c) Galena is one of the last sulfide minerals to precipitate and occurs mainly as open-space fillings.

Mount Brussilof and Rock Canyon Creek are not MVT deposits and consequently have different mineralogy; however, these deposits are also associated with one or several phases of dolomitization described above.

The Mount Brussilof mineralization consists mainly of sparry magnesite (>95 volume %). The main gangue minerals are dolomite, quartz, calcite, pyrite, and clay disseminated within the magnesite ore, filling fractures and veins, and occurring as open-space fillings. The first dolomitization phase converts limestone of the Cathedral Formation into dolomite (or dolostone) and predates crystallization of sparry magnesite. It is the same dolostone (i.e. the host dolostone described in point 2a above) that hosts the MVT and REE-F-Ba deposits.

Sparry dolomite, which occurs predominantly as fracture, vein and vug fillings, crosscuts sparry magnesite and, therefore, postdates it. Locally, REE, beryllium, and niobium minerals (e.g. fersmite, niobium-bearing rutile, goyazite, euclase), and pink or pale green micas line cavities or are enclosed in dolomite. These exotic minerals postdate the sparry magnesite and the sparry dolomite. The magnesiumrich clinochlore zone postdates the sparry magnesite and the sparry dolomite; however, its timing relative to the exotic minerals (i.e. REE, Be, and Nb minerals) is not known.

Minerals identified in the mineralized zone of the Rock Canyon Creek REE-F-Ba deposit are dolomite, fluorite, barite, pyrite, quartz, K-feldspar, calcite, porous apatite, REE fluorocarbonates and REE phosphates (Hoshino et al., 2017a, b; Akam et al., 2019). Bastnäsite, synchysite, and parisite are the main fluorocarbonates, and monazite and crandallite group minerals are the main REE phosphates (Hoshino et al., 2017a, b; Akam et al., 2019). The main REE-bearing minerals are spatially associated with, and are contemporaneous and/or postdate, barite and fluorite (which is considered a guide to ore at this deposit). Several (three or four) generations of pyrite were recognized at Rock Canyon Creek. The latest pyrite consists of pyritohedrons that contain numerous mineral inclusions (REE fluorocarbonates) and is interpreted to postdate the REE fluorocarbonates. Pyritohedrons are also present at Mount Brussilof and at several MVT deposits (e.g. Kicking Horse and Monarch).

Constraints from carbon, oxygen, and strontium isotopes in carbonate minerals

When combined with mineral chemistry and fluidinclusion data of host, altered, and mineralized carbonate rocks, C, O, and Sr isotopes can provide important constraints on the sources of mineralizing fluids and the origin and nature of dolomitization associated with mineralization.

To constrain the origin(s) and nature of the fluid flow through the region, several studies have examined dolomites from the Rocky Mountains (Nesbitt and Muehlenbachs, 1994; Yao and Demicco, 1997; Nelson et al., 2002; Paradis and Simandl, 2019) and the adjacent Western Canada Sedimentary Basin (cf. Morrow et al., 1986, 1990; Qing and Mountjoy, 1994; Wendte et al., 1998; Machel and Cavell, 1999; Al-Aasm et al., 2000; Lonnee and Al-Aasm, 2000; Nelson et al., 2002; Al-Aasm, 2003; Mrad, 2016). Here we report new data from carbonate phases associated with dolomitization and mineralization for selected MVT deposits (Monarch, Kicking Horse, Oldman, Munroe, Boivin, Hawk Creek, and Shag), a magnesite deposit (Mount Brussilof), and a REE-F-Ba deposit (Rock Canyon Creek) in the southern Rocky Mountains and compare them to one another. All carbonate rocks show large variations in $\delta^{18}O_{VPDB}$ (-9.0 to -22.5‰) and smaller variations in $\delta^{13}C_{VPDB}$ (+1.2 to -2.9‰), except for late calcite and sparry-saddle dolomites at Munroe and Boivin, which have lower $\delta^{13}C_{VPDB}$ values (Fig. 10, 15). The anomalously low $\delta^{13}C_{VPDB}$ values (-3.4 to -8.6‰) at Munroe and Boivin are from sparry and saddle dolomites associated with sphalerite and suggest that the dolomites incorporated ¹³C-depleted carbon, which can be derived from the microbial or thermal breakdown of organic matter. In this case, the low $\delta^{13}C_{VPDB}$ values are attributed to a mixture of organic- and host carbonate–sourced carbon.

The host limestone and dolostone of all the deposits are slightly depleted in ¹⁸O relative to the range of values for Cambrian and Devonian marine carbonate rocks established by Veizer et al. (1999), but they have similar $\delta^{13}C_{VPDB}$ values (Fig. 10, 15). This suggests that host carbonate $\delta^{13}C_{VPDB}$ values were buffered and that increasing temperatures produced the depleted $\delta^{18}O_{VPDB}$ values (Fig. 10), following the trend of Choquette and James (1987). Limited strontium isotope values for least-altered host limestone and dolostone from this study are available at the time of writing this paper. The dolomitic limestone at Hawk Creek has a 87Sr/86Sr value of 0.70964, which is similar to Cambrian marine carbonate rocks. The 87Sr/86Sr values of Devonian dolostone and dolomitic limestone at Oldman (0.71034-0.71044) and Rock Canyon Creek (0.70862–0.70866) are slightly higher than, and similar to, respectively, Devonian marine carbonate rocks (0.70763-0.70889; Veizer et al., 1999), and are below the maximum Sr isotope ratio of basinal shale (MASIRBAS; 0.7120; Machel and Cavell, 1999); therefore, it is likely that these carbonate rocks have inherited the primary strontium isotope composition of the Cambrian and Devonian seawater from which they precipitated.

The $\delta^{18}O_{_{VPDB}}$ and $\delta^{13}C_{_{VPDB}}$ values for replacive, saccharoidal, and sparry-saddle dolomites from individual deposits form clusters that are distinct from corresponding host rocks (Fig. 10). This is summarized on Figure 15 by small overlap between fields of MVT dolomites associated with mineralization and host dolostone. Typically, sparry and saddle dolomites have lower $\delta^{18}O_{\text{VPDB}}$ and $\delta^{13}C_{\text{VPDB}}$ values; the latter can be substantially lower in some cases (e.g. Munroe and Boivin deposits). Depletion in ¹⁸O is commonly explained by precipitation from, or interaction with, hydrothermal fluids at higher temperature relative to diagenetic dolomite. This phenomenon has been observed in other MVT and hydrothermal deposits around the world (e.g. Pine Point and Prairie Creek in the Northwest Territories, Canada; Nanisivik in Nunavut, Canada; Cadjebut in Australia), where it has been attributed to increased fluid-rock interaction (Adams et al., 2000) and elevated temperatures of dolomite formation caused by greater burial depths or interaction with hotter mineralizing fluids (Tompkins et al., 1994; Davies and Smith, 2006; Paradis, 2007a). The homogenization temperatures measured from fluid inclusions trapped in sphalerite associated with these dolomite phases are from 102 to 120°C at Monarch and 187°C at Shag (Kontak et al., this volume);



Figure 15. Plot of $\delta^{13}C_{VPDB}$ versus $\delta^{18}O_{VPDB}$ showing the fields for dolostone hosting Mississippi Valley–type (MVT) deposits, dolomite associated with MVT sulfide mineralization (also includes magnesite deposit), host carbonate rocks to the Rock Canyon Creek REE-F-Ba deposit, carbonate rocks associated with mineralization at Rock Canyon Creek, altered dolostone at Rock Canyon Creek, and one sample of saddle dolomite at Rock Canyon Creek. Fields for southern British Columbia carbonatites (Simandl et al., 2018; G.J. Simandl et al., work in progress), and primary igneous carbonaties (established by Taylor et al. [1967]) are shown for reference. The fields for Cambrian marine carbonates (CMC) and Devonian marine carbonates (DMC) are *after* Veizer et al. (1999). All isotope values were reported relative to the Vienna Pee-Dee Belemnite (VPDB) standard.

however, the pressure correction for these temperature values raises the temperature of formation to approximately 200°, which is higher than the temperature range typical of MVT deposits (70-170°C; Leach et al., 2005; Wilkinson, 2014). The salinity data for sphalerite-hosted inclusions are variable, with one group containing from 1 to 6 weight % NaCl equivalent and another group at approximately 20 weight % NaCl equivalent (Kontak et al., this volume). The high salinity values agree with classic MVT deposits worldwide but the low salinity values are in contrast (i.e. 13-28 weight % NaCl equivalent; Leach et al., 2005; Wilkinson, 2014); however, Kontak et al. (this volume) note that in rare cases (<0.5% of global data, n = 598; Bodnar et al., 2014), values to approximately 4 weight % NaCl equivalent have been reported. These data clearly suggest that the nature of the hydrothermal fluids varied as it interacted with the carbonate host rocks. The temperatures and $\delta^{18}O_{VPDB}$ values support a hydrothermal environment where the fluid-rock interaction evolved from an early fine- to medium-grained

replacive dolomite to later, coarser dolomites (saccharoidal and sparry-saddle) replacing and filling open spaces. The wide salinity range in ore-stage fluids supports a fluid mixing model with the local involvement of meteoric water (cf. Kontak et al., this volume).

The ⁸⁷Sr/⁸⁶Sr values of the replacive and sparrysaddle dolomites in MVT deposits (0.70879–0.71484) vary from similar to their respective marine carbonate rocks to higher values than MASIRBAS. In the Western Canada Sedimentary Basin, Machel and Cavell (1999) attribute high ⁸⁷Sr/⁸⁶Sr values, particularly those above 0.7120, to the introduction of radiogenic strontium by fluids that had interacted with siliciclastic rocks located in the Rocky Mountains.

Carbon and oxygen isotope values of magnesite and sparry dolomite from Mount Brussilof plot in the same field as replacive dolomite and sparry dolomite defined by dolomites of Monarch and Kicking Horse deposits (Fig. 10). They are depleted in ¹⁸O relative to the range of values for Cambrian and Devonian marine carbonate rocks established by Veizer et al. (1999), but have similar $\delta^{13}C_{VPDB}$ values (Fig. 10, 15). Magnesite has ${}^{87}Sr/{}^{86}Sr$ values from 0.70866 to 0.70996 (av. = 0.70922, n = 3), which is consistent with published values for middle Cambrian marine carbonate rocks (approximately 0.70887–0.70941; Veizer et al., 1999). Sparry dolomite associated with veins and vugs in the magnesite ore has higher values (0.71076–0.71469; av. = 0.71261, n = 4), which suggests the addition of ${}^{87}Sr$ derived from clastic rocks or other sources.

Most dolomite samples associated with REE-F-Ba mineralization at Rock Canyon Creek have the same $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{\text{VPDB}}$ values and plot in the same field as determined by Zhu (2000) for dolomites associated with mineralization (Fig. 12). One saddle dolomite analysis has a lower $\delta^{13}C_{VPDB}$ value and plots outside this field but lies on a linear trend that includes altered dolostone with fluorite and late calcite breccia-matrix and veins (\pm fluorite). The $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values of dolomite associated with mineralization at Rock Canyon Creek (our data; reddish field on Fig. 15) plot outside the field of primary igneous carbonatite established by Taylor et al. (1967; δ^{18} O ≈ -24 to -21‰ and δ^{13} C ≈-8 to -5%) and Keller and Hoefs (1995; $\delta^{18}O\approx-24$ to -20‰ and $\delta^{13}C \approx -8$ to -4‰). These $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values are also slightly higher than those corresponding to carbonatites of southern British Columbia (G.J. Simandl et al., unpub. data, 2020), which includes the Upper Fir, Verity, Roadside, Serpentine Creek, and Mount Grace carbonatites. The field for dolomite that is related to Rock Canyon Creek mineralization lies within the same fields as sparry and saddle dolomite associated with MVT mineralization (except for Munroe and Boivin) as defined in this study and studies by Nesbitt and Muhlenbachs (1994) and Yao and Demicco (1997) in Figure 12.

The 87Sr/86Sr values of mineralized and altered dolomites (0.70588-0.7093) at Rock Canyon Creek are identical or lower than their Devonian marine carbonate rocks (Fig. 11). They are higher than values of primary igneous carbonatites worldwide (e.g. Montviel, Canada (Nadeau et al., 2018); Kovdor, Russia (Zaitsev and Bell, 1995; Verhulst et al., 2000); Fen, Norway, and Blue River district, Canada (Mitchell et al., 2017; Rukhlov et al., 2018; Cimen et al., 2019)); and carbonatites of the eastern Cordillera (Rukhlov et al., 2018; Cimen et al., 2019), and they are much lower than those of MVT and magnesite deposits (0.70879-0.71484; this study). This means that the source(s) of strontium at Rock Canyon Creek was different than those of 1) primary igneous carbonatites of the eastern Cordillera and 2) MVT and magnesite deposits of the Rockies, and that local marine carbonate rocks could have been potential sources for ⁸⁷Sr. Another possibility is that the REE-F-Ba mineralization at Rock Canyon Creek overlaps or slightly postdates MVT dolomitization and because of low fluid to rock ratio, pre-existing 87Sr/86Sr ratios in dolomite were preserved even if fluids were carbonatite-related. Alternatively, ore fluid(s) at Rock Canyon Creek may have had originally low strontium content.

On the δ^{13} C versus δ^{18} O diagram (Fig. 15), the field of dolomite from the Rock Canyon Creek mineralized zone lies on the general trend connecting the southern British Columbia carbonatite field to the field for unmineralized host carbonate rocks in the same area. This suggests that REE-F-Ba mineralization may have formed from carbonatite-related fluids that interacted with the host rocks. By itself, the significance of this trend is not conclusive because the isotopic composition of carbonates from REE-F-Ba mineralization at Rock Canyon Creek coincides with that of dolomite from MVT mineralization. This is in agreement with the hypothesis that the fluids responsible for the formation of the Rock Canyon Creek deposit may have had a hydrothermal component similar to MVT mineralizing fluid. Analytical work and interpretation of data from the Rock Canyon Creek (REE-F-Ba), MVT, and carbonatite-related hydrothermal deposits is ongoing and will allow us to confirm and reconcile observations shown in Figures 10, 11, 12, and 15, or help to identify other trends.

Constraints from sulfur isotopes in sulfide minerals

Bacterial sulfate reduction (BSR) and thermochemical sulfate reduction (TSR) of marine sulfates, either directly from brines (i.e. evaporated seawater) or from dissolved evaporites, have been proposed as explanations of the mechanism causing reduced sulfur formation in MVT deposits (Anderson and Macqueen, 1982; Leach et al., 2005, 2010; Wilkinson, 2014). The range of $\delta^{34}S_{VCDT}$ values depends on the mechanism of sulfate reduction (BSR or TSR) and whether the reduction occurs in a closed or open system. Bacterial sulfate reduction is regularly thought to explain wide ranges in $\delta^{34}S_{H_2S}$ values and negative $\delta^{34}S_{sulfide}$ values, whereas TSR is commonly believed to explain small ranges in $\delta^{34}S_{H_2S}$ values and positive $\delta^{34}S_{sulfide}$ values, similar to or less than marine sulfate composition contemporaneous in age with the host rocks.

Excluding data from Boivin ($\delta^{34}S_{VCDT} = -2.3, -2.8$, and +28.8 to +36.7‰), sulfide minerals from carbonate-hosted deposits have positive and variable $\delta^{34}S_{VCDT}$ values (+9.9 to +36.7‰) typical of MVT deposits. Mississippi Valley-type deposits are thought to form by mixing between metal-bearing basin brines and H₂S-bearing brines at the depositional sites (Anderson, 1975; Leach et al., 2005; Dewing et al., 2007; Paradis et al., 2007). A variation to this model proposes that the metal- and sulfate-rich basin brines encounter an organic-rich permeable carbonate unit, where in-situ sulfate reduction occurs in the presence of hydrocarbons as a reducing agent (Anderson and Macqueen, 1982; Leach et al., 2005; Paradis et al., 2007). Bitumen was observed locally at the Munroe and Shag deposits (e.g. Kontak et al., this volume), suggesting that at one time, hydrocarbons were present at some, if not all, MVT deposits. It is, therefore, possible that marine seawater sulfate was reduced by organic matter (hydrocarbon) reducing agents (Anderson and Macqueen, 1982; Leach et al., 2005) at the ore deposition sites. The range of $\delta^{34}S_{VCDT}$ values displayed by all sulfide minerals suggests a common source of sulfur, i.e. marine sulfates. Derivation of sulfur from Cambrian seawater (approximately +26 to +35%; Claypool et al., 1980; Kampschulte and Strauss, 2004) or Late Devonian to early Carboniferous seawater (approximately +23 to +24%, but values can rise up to +30%; Claypool et al., 1980; Kampschulte and Strauss, 2004; Bottrell and Newton, 2006; Shanks, 2014) is compatible with most of the $\delta^{34}S_{VCDT}$ values measured in our studied deposits at their respective host rock ages. Our $\delta^{34}S_{VCDT}$ measurements and their host rock ages are plotted in Figure 16 with the secular seawater sulfate curve and mean sedimentary pyrite composition produced by BSR. On this diagram, the $\delta^{34}S_{VCDT}$ values of the sulfide minerals are plotted according to the ages of their respective host rocks.

Except for the Shag, Munroe, and Boivin deposits, all our $\delta^{34}S_{VCDT}$ values plot within the likely range of sulfide mineral compositions produced by TSR of seawater-derived sulfate (blue-shaded field in Fig. 16; Kiyosu and Krouse, 1990). These $\delta^{34}S_{VCDT}$ values (+9.9 to +36.7‰) and the temperatures of the ore fluids (102–187°C, and up to 200°C, pressure corrected) suggest that TSR with a fractionation of approximately 0 to 15‰ was the dominant process that controlled the reduced formation of sulfur; how-ever, because there is such a large range of $\delta^{34}S_{sulfide}$ values within some deposits locally, and across all deposits of the Rocky Mountain foreland belt, it is likely that a mixture of



Figure 16. Relationship of sulfur isotope values of carbonate-hosted deposits of the southern Canadian Rocky Mountains to the age of the host rocks. Also plotted are the marine sulfate composition (or ambient seawater curve; thick blue line; Farquhar et al., 2010), the likely range of sulfide compositions produced by thermochemical sulfate reduction (TSR) of seawater-derived sulfate at 150°C (blue shaded field; Kiyosu and Krouse, 1990), the mean sedimentary pyrite composition (thick black line; Farquhar et al., 2010) produced by bacterial sulfate reduction (BSR). Note that the curve of marine sulfate evolution (thick blue line) versus time represents average values and that estimates of uncertainty are not shown. Sulfur in most Mississippi Valley–type deposits is consistent with an origin from seawater sulfate, reduced by TSR. *Modified from* Wilkinson (2014).

TSR and BSR processes occurred. For example, the sulfur in sphalerite from Boivin has negative $\delta^{34}S_{\text{VCDT}}$ values (–2.3 and -2.8‰) and may have been sourced through BSR in the presence of hydrocarbons, whereas the adjacent Munroe deposit has galena and sphalerite with much higher $\delta^{34}S_{\scriptscriptstyle VCDT}$ values (+28.8 to +36.7‰) that plot outside the blue-shaded field in Figure 16, above the ambient seawater curve. Such a large difference in values between Boivin and Munroe is typical of BSR and situations where Rayleigh distillation process may have occurred in a partially closed system with a limited sulfate supply reservoir (e.g. Large et al., 2005; Shanks, 2014). Another hypothesis is that reduced sulfur was generated by two different mechanisms at Boivin and Munroe, BSR in an open system at Boivin and TSR at Munroe. The $\delta^{34}S_{\text{sulfide}}$ values at Shag (+15.5 to +19.2‰) are approximately 10 to 15‰ lower than contemporaneous seawater sulfate and they plot outside the blue-shaded field in Figure 16. This suggests that a portion of the sulfur at Shag might have derived from BSR processes.

The Rock Canyon Creek deposit, hosted in Middle Devonian Cedared and Burnais formations containing gypsum horizons, has a $\delta^{34}S_{VCDT}$ barite value of +31.7‰, comparable to $\delta^{34}S_{VCDT}$ values measured from marine evaporite minerals (e.g. anhydrite) in Upper Devonian formations in Alberta (+20.6 to +31.7‰; Davies and Wendte, 2005).

All the deposits mentioned above are epigenetic in nature and consequently are younger than their host rocks. The inherent uncertainty about their ages of formation makes it difficult to relate their δ^{34} S values to the contemporaneous seawater sulfate values, and this adds uncertainties and complexity to our interpretation; therefore, the interpretations presented above are not final and are dependent on additional ages of carbonate-hosted mineralization and sulfur analyses.

Some of the sulfide minerals (coeval sphalerite and galena) in MVT deposits appear to be in textural equilibrium and are, therefore, amenable to isotopic equilibrium temperature calculations. Sphalerite-galena pairs at the Oldman deposit produce isotopic equilibrium temperatures from 92 to 138°C (using the equations of Grootenboer and Schwarcz (1969), Kajiwara and Krouse (1971), Czamanske and Rye (1974), and Liu et al. (2014)). Temperatures for sphalerite-galena pairs were calculated between 138 and 254°C for the Monarch and Kicking Horse deposits, but much lower temperatures (22-86°C) were calculated for Munroe. The low calculated temperatures for the Munroe deposit run counter to the argument for isotopic equilibrium between sphalerite and galena, but the other listed temperatures are acceptable for MVT systems and are consistent with the range of temperatures obtained from fluid-inclusion analyses.

Constraints from lead isotopes in sulfide minerals

Lead isotopic analyses were undertaken to identify possible lead sources (and, by inference, other metals), to constrain timing of mineralization and assess possible genetic links among the deposits. Lead isotope analyses are plotted on the shale curve of Godwin and Sinclair (1982), a growth curve unique to the ancient western margin of North America, and other growth curves (e.g. upper crust, orogene, and mantle growth curves of Zartman and Doe, 1981).

When plotted on these diagrams, our data form three clusters, each defined by specific deposits. The least radiogenic group of samples (cluster 1) is from the Monarch, Kicking Horse and Munroe deposits. On the ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb diagram (Fig. 14a), the samples form a tight group plotting between the orogene and upper crust curves. On the ²⁰⁷Pb/²⁰⁶Pb versus ²⁰⁸Pb/²⁰⁶Pb diagram, the samples plot as a tight group just below the upper crust and shale curves (Fig. 14b). This suggests that lead was either from a single, well-homogenized source or that the mineralizing process caused homogenization and mixing of lead in the deposits.

The second cluster (cluster 2), consisting exclusively of samples from the Shag deposit, forms a subvertical trend above the shale and upper crust curves on the ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb diagram (Fig. 14a). On the ²⁰⁷Pb/²⁰⁶Pb versus ²⁰⁸Pb/²⁰⁶Pb diagram (Fig. 14b), it forms a tight cluster sitting on or slightly below the shale curve. This suggests a homogeneous lead source, but with a more prominent crustal influence (e.g. lead from the weathering and erosion of detrital sediments derived from crustal sources) than cluster 1.

Samples from Hawk Creek, Mount Brussilof, Oldman, and Munroe deposits form cluster 3, and are the most radiogenic (Fig. 14a). These samples plot above and to the right of the shale and upper crust curves, within the Cordilleran carbonate trend defined by carbonate-hosted Zn-Pb deposits and occurrences of the northern Rocky Mountains, the Mackenzie platform, and Western Canada Sedimentary Basin (cf. Nelson et al., 2002). The Cordilleran carbonate trend forms a large field and includes some of the most radiogenic lead isotope compositions of the Cordillera (Nelson et al., 2002). This Cordilleran-carbonate trend is interpreted as a single linear trend (Godwin et al., 1982) or as a series of closely spaced trends (Morrow and Cumming, 1982; Morrow et al., 1986, 1990). Nelson et al. (2002) interpreted it as mixing between two end members, one less radiogenic and the other extremely radiogenic. Our data for deposits in the southern Rocky Mountains extend the field of the Cordilleran carbonate trend and agree with the interpretation of Nelson et al. (2002).

The regression lines in Figure 14a and b, which includes all data from cluster 3 (the Cordilleran carbonate trend), intersects the shale curve at ca. 360 Ma and intersects clusters 1 and 2, suggesting that the lead signatures of clusters 1, 2, and 3 represent mixtures of variably radiogenic end members. One end member has to be 'unradiogenic' or poorly radiogenic, with lead isotope ratios equal to or lower than 17.4 to 17.6 ²⁰⁷Pb/²⁰⁴Pb, 15.5 to 15.6 ²⁰⁶Pb/²⁰⁴Pb, 0.8812 to 0.8933 ²⁰⁷Pb/²⁰⁶Pb, and 2.1614 to 2.1836 ²⁰⁸Pb/²⁰⁶Pb, values that correspond to the vein- and fracture-controlled carbonate-hosted sulfide-barite deposits located in the western foreland belt of the Canadian Cordillera (e.g. Lead Mountain Pb-Zn deposit; Fig. 14a, b); however, the Precambrian basement rocks could also be a source of unradiogenic lead. The other end member must be highly radiogenic with lead isotope ratios equal to or higher than the highest measured value in the Cordilleran carbonate trend. Such a highly radiogenic lead end member could be sourced from shale or other clastic rocks derived from crystalline basement rocks from deep within the basin or adjacent basins. Shale can be very radioactive due to their high uranium content and can also be enriched in various other metals, including silver, gold, copper, lead, and zinc (Coveney, 2003; Gregory et al., 2015; Peter et al., 2018; Henderson et al., 2019) and may be the source of the radiogenic lead and, by inference, other metals in carbonate-hosted Zn-Pb deposits. In British Columbia, the platforms hosting the carbonate-hosted deposits are bounded to the west by shale basins such as the Kechika trough, which hosts SEDEX Zn-Pb deposits. The metals could have been (re)-mobilized in deep-circulating basin brines as the shales underwent burial and maturation. Fluid movement along deep-seated faults at basin-platform margins may have transported metals into the subjacent platform carbonates, where sulfide metals were ultimately precipitated.

Age of mineralization

The ages of carbonate-hosted mineralization, such as MVT deposits, are difficult to determine due to their mineralogy, the paucity of reliable dating methods for their minerals, and the genetic relationship of the sulfide minerals to associated datable minerals is commonly unclear. Dating mainly relies on paleomagnetism and sphalerite Rb-Sr geochronology; however, these methods produce contradictory ages for Zn-Pb mineralization in the Canadian Rocky Mountains (Fig. 17). Paleomagnetic dating typically produces young ages (<100 Ma), implying that mineralization formed in response to compression during orogenesis, specifically during the Late Cretaceous to Paleocene (approximately 80-45 Ma) Laramide Orogeny (Symons et al., 1993, 1998; Smethurst et al., 1999). It has been shown that the magnetic remanence of carbonate rocks and their mineral deposits in the Rocky Mountains are constant along a 500 km strike length and this pervasive chemical remanence overprinted the primary remanence (Enkin et al., 2000). We thus surmise that the remagnetization of sulfide minerals within deposits of the Rocky Mountains has the character of a regional overprint and is not related to the processes of dolomitization and mineralization.

The sphalerite Rb-Sr isotopic dating method typically produces ages older than paleomagnetic ages. At the Robb Lake MVT deposit in the northern Rocky Mountains, sphalerite Rb-Sr dating indicates that mineralization occurred during the Paleozoic (Nelson et al., 2002), consistent with the Late Devonian age (362 ± 9 Ma) for MVT Zn-Pb mineralization at Pine Point (Nakai et al., 1993). These ages favour mineralization during a Devonian to Mississippian extensional tectonic regime along the continental margin, rather than the Cretaceous compressional orogenic models suggested by paleomagnetic dating. Sphalerite Rb-Sr geochronology has also been tested in deposits of the southern Cordillera, but with unsatisfactory results (e.g. Robb Lake at 348 ± 130 Ma; Nelson et al., 2002).

We have also attempted to date sulfide mineralization using Re-Os geochronology on pyrite. This method has been successfully applied to selected MVT deposits in the northern Rocky Mountains, the Mackenzie Mountains, and the Kootenay Arc of southern British Columbia (D. Hnatyshin et al., work in progress; Paradis et al., 2020). The Robb Lake and Prairie Creek Zn-Pb deposits located in the northern Rocky Mountains and the Mackenzie Mountains have been dated by pyrite Re-Os geochronology and produce Late Devonian to mid-Carboniferous ages (Paradis, 2007b; Hnatyshin, 2018; D. Hnatyshin et al., work in progress). These ages corroborate the earlier findings of Nelson et al. (2002) and support the theory of an extensional western continental margin and the formation of sulfide deposits during that period.

Further south, carbonate-hosted MVT Zn-Pb deposits located in the Kootenay Arc, the westernmost flank of the ancient Pacific margin of North America, have been dated by pyrite Re-Os geochronology with variable success (Paradis et al., 2014; Hnatyshin, 2018; Paradis et al., 2020). Broad ages of Late Devonian to early Carboniferous were obtained for the Salmo MVT deposits (Paradis et al., 2014; Hnatyshin, 2018), and an age of 512 \pm 17 Ma was obtained for the Pend Oreille Zn-Pb deposit Paradis et al. (2020). This carbonate-hosted Zn-Pb deposit is located south of the Salmo deposits in the Kootenay Arc and is hosted by the middle Cambrian to Early Ordovician Metaline Formation (Paradis et al., 2020). The age of 512 Ma is new for carbonate-hosted Zn-Pb deposits of the southern Cordillera and suggests that mineralizing event(s) related to extensional tectonic regimes occurred along the continental margin during the Cambrian to Ordovician. Rifting episodes that occurred along the margin during the Cambrian coincided with the breakup of Laurentia from the supercontinent Rodinia (Colpron et al., 2002; Lund et al., 2003, 2010; Nelson et al., 2013).

These results indicate that at least two periods of MVT mineralization occurred and formed in response to tectonic activity along the western continental margin of North America during the Paleozoic: one period in the middle to late Cambrian and another one in the late Devonian to middle Carboniferous.



Figure 17. Summary of known radiometric and paleomagnetic ages of carbonate-hosted Zn-Pb mineralization and their host rocks within the Canadian Cordillera (*modified from* Leach et al., 2001); NA: North America. ¹Data from Nelson et al. (2006); ²radiometric data from various sources and compiled by Millonig et al. (2012); ³radiometric data (Rb-Sr) from Nakai et al. (1993), paleomagnetic data from Symons et al. (1993); ⁴radiometric data (Rb-Sr) from Nelson et al. (2002), paleomagnetic data from Smethurst et al. (1999); ⁵radiometric data (Re-Os) from Hnatyshin (2018) and D. Hnatyshin et al. (work in progress); ⁶radiometric data from Pannalal et al. (2007), radiometric data from Paradis et al. (2020); ⁸paleomagnetic data from Symons et al. (1998).

Based on poorly constrained geological evidence, Zhu (2000) suggested that mineralization postdated the Laramide Orogeny. At the time of writing this paper, we do not have a confirmed age on the REE-F-Ba mineralization at Rock Canyon Creek.

SUMMARY AND CONCLUSIONS

The following is a summary of our current observations on the geology and geochemical characteristics of selected carbonate-hosted deposits of southern British Columbia (MVT, magnesite, and REE-F-Ba). We compare these deposits, identify some outstanding questions, and suggest future extensions to this work:

- The transition from shallow-water platform carbonate rocks to deeper-water basin facies that existed at different times during the Paleozoic exerted a control on the location of MVT and magnesite, and possibly REE-F-Ba deposits. Several deposits (e.g. Monarch, Kicking Horse, Mount Brussilof, and Shag) are associated with the Kicking Horse Rim, a Precambrian, fault-controlled, paleotopographic high that extends through the southern Rocky Mountains (Fig. 1). The Kicking Horse Rim is a physiographic feature over which shallow-water platform carbonate rocks to the east transition into a complex coeval succession of deep-water basin and slope lithofacies to the west. The transition from platform carbonate rocks to basin facies along the margin corresponding to the Kicking Horse Rim was an ideal location for fluid flow given the likely presence of reactivated, deep-seated basement faults and the permeability contrast between shales and carbonate rocks. McMechan (2012), who identified two regional cross-belt Paleoproterozoic and Archean basement transverse structures (the Red Deer zone and the Vulcan Low), stated, "greatest enhancement of hydrothermal flow and mineralization occurred near the intersection of basin-parallel and transverse structures" (p. 693).
- Deposits are hosted in dolomitized limestone (i.e. dolostone), which formed along the platform margin and has regional distribution. Most of the studied deposits are associated with syn- to post-depositional phases of dolomitization represented by replacive, sparry, and saddle dolomites. Dolomitization resulted from hydrothermal fluid migration along fault systems and strata with enhanced porosity and permeability.
- Dolomitizing fluids responsible for dolomites associated with MVT and sparry magnesite deposits were hydrothermal fluids, modified by interaction with clastic rocks, and expelled from deep burial settings by tectonic stresses as exemplified by high temperatures, $\delta^{18}O_{VPDB}$ values of -20.0 to -9.8‰, and $^{87}Sr/^{86}Sr$ ratios of 0.70949 to 0.71484, which are above the middle Cambrian and

Middle Devonian marine carbonate values reported by Veizer et al. (1999) and close to or above the MASIRBAS value (0.7120; Machel and Cavell, 1999).

- Sulfur isotope values of sulfide minerals show wide variation within a deposit (e.g. +28.8 to +36.7 at Munroe) and among different deposits (e.g. $\delta^{34}S_{VCDT}$ values across all deposits range from -2.8% to +36.6% [n = 53], with most values falling between +9.9 and +36.6% [n = 51]). The wide range in $\delta^{34}S_{VCDT}$ is typical of classic MVT deposits among different districts worldwide. Our data indicate that reduced sulfur formation predominantly occurred through TSR of coeval seawater sulfate for several deposits (e.g. Kicking Horse, Monarch, and Hawk Creek deposits); however, BSR also occurred locally (e.g. at the Boivin deposit).
- The $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values for replacive, sparry, and saddle dolomites associated with MVT, sparry magnesite, and REE-F-Ba deposits compare well with the hydrothermal dolomites studied by Nesbitt and Muehlenbachs (1994) and Yao and Demicco (1997) and other MVT deposits in the northern Rocky Mountains (e.g. Robb Lake; Nelson et al., 2002). The homogenization temperatures, measured from fluid inclusions trapped in sphalerite associated with these dolomites (approximately 160-240°C, pressure corrected to 1 kbar; Kontak et al., this volume), support a hydrothermal origin. Although the MVT, magnesite, and Rock Canyon Creek deposits have similar $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values for replacive, sparry, and saddle dolomites, their 87Sr/86Sr values are slightly different. Rock Canyon Creek dolomites have lower 87Sr/86Sr values than those in MVT and magnesite deposits and are similar to those in Devonian marine carbonate rocks. The REE component of Rock Canyon Creek mineralization may have precipitated from distal carbonatite-related fluids.
- Ages of mineralization support the inference that mineralization occurred intermittently and in more than one stage during the Paleozoic, i.e. middle to late Cambrian and Late Devonian to middle Carboniferous.

Implications for exploration

Integration of detailed fieldwork and petrographic, mineralogical, isotopic, and fluid-inclusion analyses of sulfide and gangue minerals from carbonate-hosted deposits of the southern Rocky Mountains can provide important insights. For example, we can gather information on the origin and nature of dolomitization (associated with MVT, magnesite, and REE-F-Ba mineralization) and the sources and temperatures of mineralizing fluids. This facilitates the improvement of and helps to establish genetic models for the carbonate-hosted deposits of the Rocky Mountains. Mineral exploration is guided by deposit models, so producing accurate and up-to-date genetic models is essential for the industry to formulate the most efficient exploration programs targeting these deposits in the Canadian Cordillera and elsewhere in Canada.

Several key factors, identified during the project and highlighted in this review, can be applied to improve the success rate of the search for new deposits:

- Deposits are more common in proximity to the shallow-water carbonate platform margin, at the transition into deeper-water basin rocks. This structurally controlled transition was most likely the locus of deep-seated basement fault structures.
- Middle to upper Cambrian and Upper Devonian dolostones with zones of high primary and secondary porosity (i.e. breccias, vugs, fractures, and veins) associated with hydrothermal dolomites are optimal targets.
- There is a generalized paragenesis consisting of widespread dolomitization of marine carbonate rocks followed by different types of hydrothermal dolomite formation (e.g. saccharoidal, sparry, and saddle dolomites) and sulfide deposition (mainly in the form of carbonate replacement by sphalerite, galena, and pyrite), and subsequent cavity- and fracture-filling carbonate rocks.
- Hydrothermal dolomites typically have lower $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values and $^{87}Sr/^{86}Sr$ values similar to or higher than their respective host dolostones. Other geochemical characteristics of these dolomites (e.g. higher Fe and Zn content, and REE content with positive Eu anomalies associated with convex upward patterns) are listed in Simandl et al. (this volume).
- Two main episodes of formation of mineralization and associated hydrothermal dolomitization were the middle to late Cambrian and Late Devonian to middle Carboniferous.

Future work and outstanding questions

This paper describes and compares the main geological and geochemical characteristics of selected carbonate-hosted sulfide deposits of the Rocky Mountains of southern British Columbia. A full discussion of the ore-forming processes and the genetic links between the deposits will be the subject of upcoming peer-reviewed publications.

Additional isotopic analyses (e.g. O, C, Sr, S, Pb) of sulfide, sulfate, and carbonate minerals, combined with fluid-inclusion microthermometry of ore and gangue minerals and clumped isotopes on carbonate rocks is planned, which will provide more information on the chemical composition, temperatures, and salinities of ore-forming fluids and associated dolomitization, and constrain the sources of ore-forming fluids and metals in hydrothermal mineral deposits. A preliminary in-situ secondary ion mass spectrometry (SIMS) measurement of δ^{34} S (i.e. from sphalerite, pyrite) in one sample from the Kicking Horse deposit (Kontak et al., this volume), verifies the similarity of results to the conventional bulk-type analyses performed on this deposit during this study. Additional SIMS analyses will, therefore, be done on a larger selection of samples from Kicking Horse and other deposits.

The sources of metals in these deposits are still not completely resolved, and several possibilities exist. Lead isotope analyses of MVT deposits imply that local shales, basement rocks, or basement-derived sedimentary lithological units are all candidates for the sources of lead and, by inference, other metals in MVT deposits. Samples from Rock Canyon Creek will, therefore, be analyzed and compared to MVT and magnesite deposits.

In-situ trace element analyses of carbonate and sulfide minerals by laser ablation-inductively coupled plasmamass spectrometry (LA-ICP-MS) will provide insight into dolomite- and ore-forming fluid chemistry and origin. Preliminary analyses of carbonate minerals (Simandl et al., this volume) show significant variations in REE content among the carbonate-hosted Zn-Pb deposits of the southern Canadian Cordillera. This suggests that some of the carbonate minerals may have crystallized directly from hydrothermal fluids and previously formed carbonate minerals, possibly of sedimentary origin, re-equilibrated with ambient fluids during diagenesis, deep burial, and/or metamorphic recrystallization. The LA-ICP-MS analyses of sulfide minerals from the studied MVT deposits and other MVT deposits of the Canadian Cordillera are ongoing.

Our work, results, and interpretations represent progress in the study of carbonate-hosted deposits in the Canadian Cordillera and their likely age; however, disagreement on the age of most MVT deposits of the Rocky Mountains in southern British Columbia still exists. Unfortunately, attempts to obtain ages from selected carbonate-hosted deposits of the southern Rocky Mountains using Re-Os geochronology on pyrite have only been moderately successful. The Monarch, Kicking Horse, Rock Canyon, and Hawk Creek deposits do not contain enough Re (approximately 0.5 ppb) and Os (approximately 5 ppt) for dating analyses; therefore, Re-Os isotopic analyses of pyrite-rich samples from other carbonate-hosted deposits (subject to availability) will be used to help constrain the age of sulfide mineralization and improve the genetic model(s) of these deposits.

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