Geological setting of the Rock Canyon Creek REE-fluorite deposit, British Columbia, Canada

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Recommended citation: Green, C., Simandl, G.J., Paradis, S., Katay, F., Hoshino, M., Kon, Y., Kodama, S., and Graf, C., 2017. Geological setting of the Rock Canyon Creek REE-fluorite deposit, British Columbia, Canada In: Geological Fieldwork 2016, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2017-1, pp. 195-203.

Abstract

The Rock Canyon Creek REE-fluorite deposit is in the Foreland Fold and Thrust belt of the Canadian Cordillera, 300 metres east of the Munroe Lake thrust fault which, in the deposit area, divides the Main Ranges from the Front Ranges of the Canadian Rocky Mountains. A literature review and preliminary fieldwork indicate that the deposit is hosted by Middle Devonian rocks of the Cedared and Burnais formations and consist mainly of dolostone, breccia, and laminated silty, calcareous gypsum. Fluorite-bearing outcrops extend across an area 3300 by 750 metres. The steeply dipping REE-fluorite zone was intersected by drilling. It may be more than 50 metres thick for more than 1100 metres along strike, and to a depth of 124 metres. It remains open along strike and dip, and its thickness locally exceeds 50 metres. Based on surface mapping and borehole logging, the deposit appears to be concordant with stratigraphy. Most of the mineralization occurs as breccias and fracture fillings in fluorite-impregnated dolostone. Fluorite concentrations vary from less than 1% to 13.5% by weight, and light REE (Ce+La+Nd) concentrations vary from trace to 2.8%. REE are hosted mainly by bastnasite-(Ce), parisite-(Ce), synchysite-(Ce), and REE-bearing phosphates. Ongoing work will focus on better characterizing the deposit to address questions about the origin of ore forming fluids and the temporal, structural, and stratigraphic relationship to Mississippi Valley-type and sparry magnesite deposits along the eastern flank of the Canadian Cordillera.

Keywords: Rare earth elements, fluorite, breccia, Cedared Formation, Burnais Formation

1. Introduction

The Rock Canyon Creek deposit, 90 kilometres northeast of Cranbrook (Fig. 1), contains rare earth elements (REE) and fluorite. The term REE is commonly used to cover lanthanides, yttrium and scandium. The geology of REE is summarized by Mariano (1989a, b, 2012), Simandl et al. (2012a), Simandl (2014), and market conditions are summarized by Simandl (2014) and Gambogi (2016 a, b). In 2015, more than 85% of REE production came from one jurisdiction (China). These elements are considered 'critical metals' due to the high risk of supply disruption, and the importance of REE for many industries, including national defense and those addressing greenhouse gas emissions (Simandl et al., 2015). Fluorspar, the commercial term for fluorite (CaF_2) is an important industrial mineral with metallurgical applications.

Of the 44 known REE occurrences in British Columbia, all but one (Riddle Creek prospect, Trofanenko et al., 2013) are in the British Columbia alkaline province, along the boundary between the Omineca and Foreland belts (Fig. 1; Pell, 1994; Simandl et al., 2012a, b). The provinces consists of intrusive and extrusive carbonatites, nepheline and sodalite syenites,

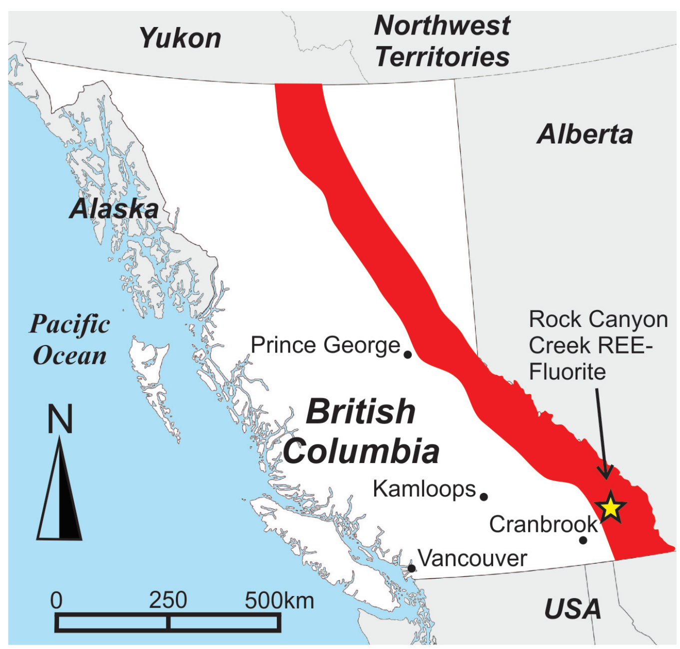

Fig. 1. Location of the Rock Canyon Creek REE-fluorite deposit. The British Columbia alkaline province as defined by Pell (1994) is in red.

ijolite series rocks, kimberlite, and numerous ultramafic and lamprophyre diatremes, breccias, and dikes (Pell, 1994). Most, if not all, of these rocks intruded Cordilleran miogeoclinal strata. The Rock Canyon Creek REE-fluorite deposit is one of the most promising REE prospects in the alkaline province. Fluorite occurrences in British Columbia were inventoried and described by Pell (1992), and the Rock Canyon Creek is one of the deposits recommended for follow-up studies (Simandl, 2009).

The purpose of this paper is to summarize the tectonic, stratigraphic, and structural setting of the deposit, and its geometry and mineralogy. It is based on a review of the literature, a field reconnaissance, and logging of core from boreholes drilled by Spectrum Mining Corporation in 2009. The paper is a prelude to more detailed field and laboratory studies directed at establishing the origin of the Rock Canyon Creek deposit and possible relationships to other carbonate-hosted deposits in eastern British Columbia.

2. Tectonic setting

The Rock Canyon Creek deposit is in the Foreland Fold and Thrust belt of the Canadian Cordillera (e.g., Gabrielse et al., 1991; Monger and Price, 2002). It lies in the footwall of the Munroe Lake thrust (Fig. 2), which divides the Main Ranges from the Front Ranges of the southern Canadian Rocky Mountains (Mott, 1989). Late Jurassic to early Tertiary thin-skinned folding and thrusting in the Rocky Mountains affected miogeoclinal and foreland basin sedimentary rocks deposited on top of crystalline Precambrian basement (e.g., Price and Fermor, 1985; Monger and Price, 2002). Several diatremes and intrusions in the region may be related to deep transverse basement structural features (McMechan, 2012). Such intrusions have not been recognized near the Rock Canyon Creek REE-fluorite mineralization.

3. Geology of the Rock Canyon Creek area

The geology of the Rock Canyon Creek area (Figs. 2, 3) was mapped by Leech (1979), Mott (1989), and McMechan and Leech (2011). The interpretation shown in Figure 2 is based largely on the work of McMechan and Leech (2011). The location of the postulated Rock Canyon Creek fault is from Mott (1989). The distribution of fluorite occurrences is from Dix (1991), and Pell (1992), and the location and extent of the main zone is based on drill hole intersections (Pighin, 2010). The stratigraphic units and the orientation of the faults have a general northwest-southeast trend.

3.1. Stratigraphy

The oldest strata in the Rock Creek Canyon deposit area are part of the McKay Group Unit A (Fig. 2; Upper Cambrian-Lower Ordovician; Mott, 1989; McMechan and Leech, 2011). This 400-600 metre thick cliff-forming unit consists of dark grey, brown-weathering, limestone and dolostone with resistant siliceous or silty laminations. Local intraformational flat-pebble conglomerates and light blue-grey-weathering nodular to lenticular chert horizons are in the upper 30 metres of the unit (McMechan and Leech, 2011). Fossil debris near the upper contact with the Glenogle Formation contains the Tremadocian (ca. 485-477 Ma) brachiopod *Nanorthis cf. N. putillus* (Mott, 1989).

The Glenogle Formation (Lower Ordovician) conformably overlies the McKay Group, and the contact is usually an abrupt planar surface (Mott, 1989). The Glenogle Formation is up to 175 metres thick, and grades upward from a graptolitic black shale to siltstone unit, to quartz arenite, to platy to thickly bedded mottled limestone and dolostone (Mott, 1989; McMechan and Leech, 2011). Black chert nodules are common in the upper carbonate rocks. The upper limestone and dolostone contain 1-2% crinoid, brachiopod, and gastropod fossil debris (Mott, 1989).

The Skoki Formation (Middle Ordovician) disconformably overlies carbonate rocks of the Glenogle Formation. About 150 metres thick, it consists of thickly bedded resistant, dark to pale grey dolostone with abundant chert nodules (10-30%), wavy laminae, and fossil debris (Mott, 1989; McMechan and Leech, 2011). The Skoki Formation is distinguished from the overlying Beaverfoot Formation by the absence of fossil coral (Mott, 1989).

The Skoki Formation is commonly overlain by a thin (<10 metres) but laterally persistent Upper Ordovician dolomite-quartz arenite unit. It may be the basal siliciclastic component of the Beaverfoot Formation (Mott, 1989) or a distinct formation, the Akanko Creek (McMechan and Leech, 2011). South of the map area, the contact between this siliciclastic unit and the underlying Skoki Formation is an angular unconformity (Mott, 1989).

A conglomerate unit (McMechan and Leech, 2011) at the base of the Beaverfoot Formation (Upper Ordovician-Lower Silurian) is overlain by pale grey, spheroidal weathering dolostones (Mott, 1989) with abundant corals (Pell and Hora, 1986) and silicified skeletal debris (crinoids and brachiopods; Mott, 1989). The combined thickness of the Akanko Creek unit and the Beaverfoot Formation is approximately 150 metres (Mott, 1989).

Hosting the Rock Creek Canyon deposit, the Cedared and Burnais formations (Middle Devonian) disconformably overlie the Beaverfoot Formation and have a combined thickness of 75-100 metres (Mott, 1989). They consist of orange-brown weathering dolostone, and pale-weathering quartz-bearing dolostone of the Cedared Formation (Fig. 4a), and breccia, and laminated grey to dark grey silty, calcareous gypsum of the Burnais Formation (Mott, 1989). The Cedared and Burnais are portrayed as a single unit on the map of McMechan and Leech (2011). Fossils and fossil debris include uncommon fish fragments, gastropod, crinoid and brachiopod debris (Mott, 1989). In the Rock Canyon Creek area they are separated from the Beaverfoot Formation by the Munroe Lake thrust fault.

The Fairholme Group (Upper Devonian), which is approximately 100 metres thick, disconformably overlies the Cedared and Burnais formations, and has been interpreted as an

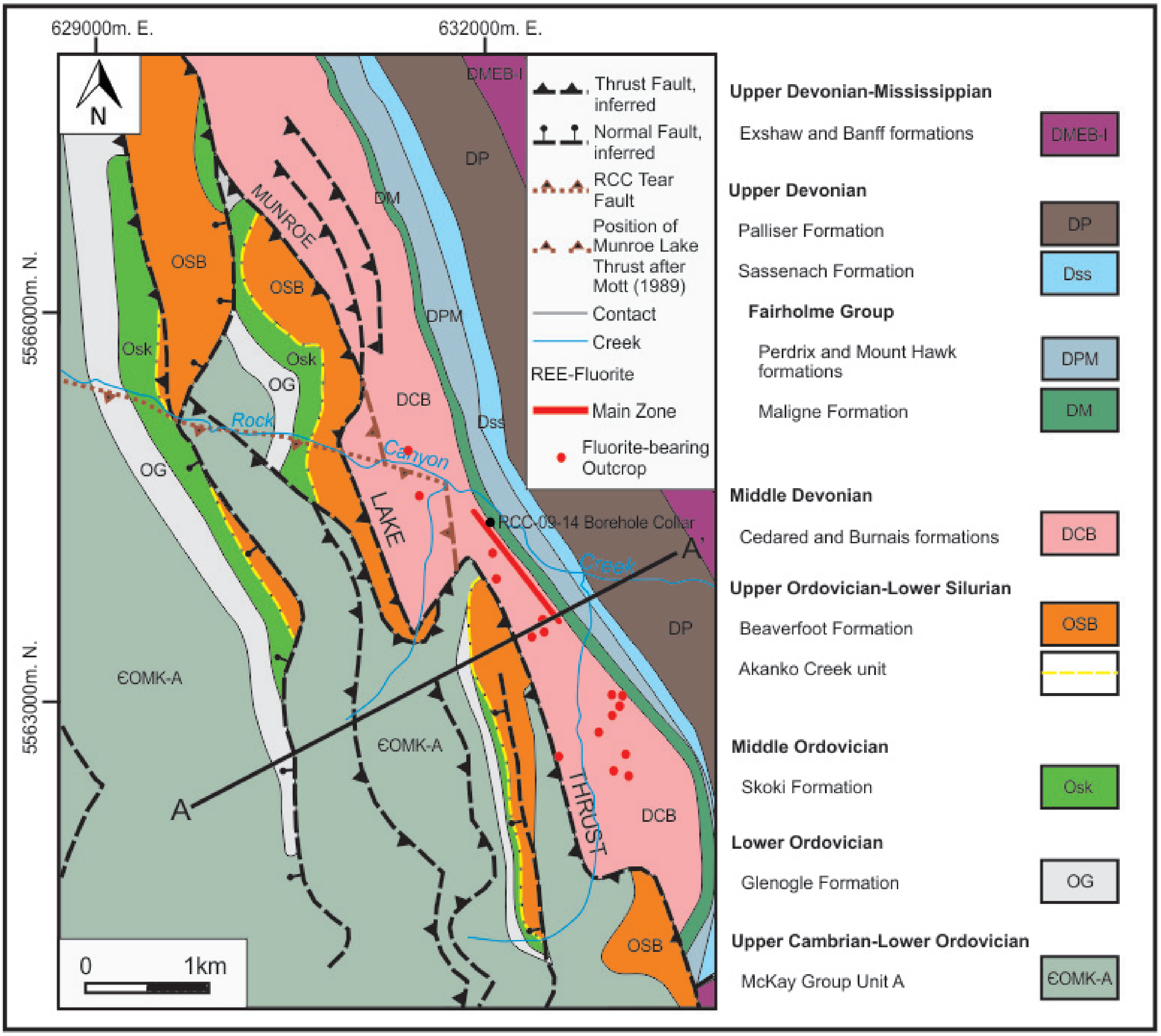

Fig. 2. Geological setting of the Rock Canyon Creek deposit. Modified after McMechan and Leech (2011). An alternative interpretation from Mott (1989) includes a west-northwest-trending fault (Rock Canyon Creek tear fault) in brown.

off-reef facies by McMechan and Leech (2011). The Fairholme Group has been further divided by McMechan and Leech (2011) into the basal Maligne Formation, and upper Perdrix and Mount Hawk formations (Fig. 2). The basal Maligne Formation is a dark-grey to black, buff weathering, fossiliferous, lime mudstone with a silty siliciclastic component. Mott (1989) also noted a late Givetian (late Middle Devonian) *disparilis* conodont zone at the base of the Fairholme in the Rock Canyon Creek area. The Perdrix and Mount Hawk formations are fissile dark grey to black calcareous, thinly bedded mudstones and shales with up to 1% fossil fragments (Mott, 1989; McMechan and Leech, 2011).

The Sassenach Formation, up to 200 metres thick at Rock Canyon Creek, is Upper Devonian and consists of siltstone and sandstone, with local argillaceous limestone near its top and base (McMechan and Leech, 2011).

The Palliser Formation (Upper Devonian) is locally divided into a lower, cliff-forming unit and an upper recessive unit. The cliff-forming unit is a light grey weathering, massive micritic limestone and dolostone, that is locally peloidal and mottled by burrows. The recessive unit consists of grey weathering, thinly bedded lime mudstone, which is similar to the upper Fairholme Group (Mott, 1989; McMechan and Leech, 2011). Regionally, the Palliser Formation may be more than 600 metres thick (Mott, 1989).

Together, the Exshaw and Banff formations (Upper

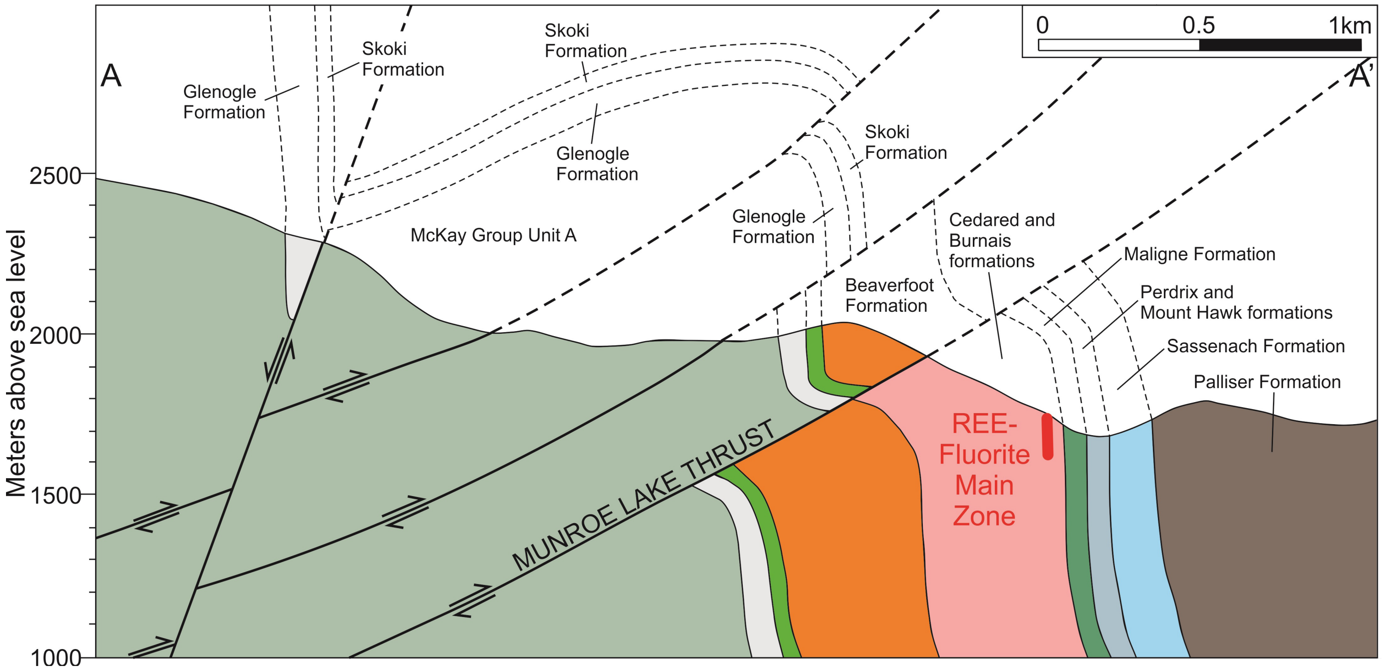

Fig. 3. Geological cross section of the Rock Canyon Creek deposit area. For section location and legend see Figure 2. No vertical exaggeration. Based on mapping by Mott (1989) and McMechan and Leech (2011).

Devonian-Mississippian) are about 1000 metres thick in the Rock Canyon Creek deposit area. The contact with the Palliser Formation is poorly exposed but sharp (Mott, 1989). The Exshaw-Banff formations consist of finely laminated, fissile shale with abundant pyrite nodules grading upwards into a brown-weathering limy shale and brown-grey shaly lime-mudstone (Mott, 1989). Regionally, the Exshaw Formation contains felsic tuffs with a ca. 363 Ma age (U-Pb zircon; Richards et al., 2002).

3.2. Structure

The predominant structural elements in the area are northeast-vergent thrusts and folds (Figs. 2, 3; Mott, 1989; McMechan and Leech, 2011). Thrust faults, including the Munroe Lake thrust, are oriented northwest-southeast and dip shallowly to the southwest (Fig. 3). A normal fault west of the Munroe Lake thrust has a similar strike to the thrusts (Fig. 2), but dips steeply southwest (Fig. 3).

Mott (1989) proposed that a northwest-striking, south-dipping tear fault (Rock Canyon Creek tear fault) follows the trend of Rock Canyon Creek, based on the observation that the Beaverfoot, Skoki, and Glenogle formations are exposed at lower elevations on the north side of the creek than on the south side. Although this putative tear fault was not included in the McMechan and Leech map (2011), its projection may connect to the Munroe Lake fault 200 metres northwest of the main REE-fluorite zone (Fig. 2). Because of the possible importance of the fault to mineralization, future fieldwork will attempt to resolve if the fault exists or not.

A pressure solution cleavage is best developed in argillaceous units of the McKay Group, and Cedared and Burnais formations. In general, fracturing and veining (calcite and quartz) appears to be inversely proportional to the intensity of cleavage development for most units, with the exception of the Cedared and Burnais formations, which display both well-developed cleavage and fracturing (Mott, 1989). Different fracture sets crosscut one another, indicating multiple generations of fracturing. Fractured rocks probably acted as a sink for material removed from nearby units by pressure solution (Mott, 1989).

Breccias in the Cedared and Burnais formations in Beaverfoot, Brisco, and Standford ranges consisting of angular fragments of limestone and dolostone in a sandy mudstone matrix, were interpreted by Belyea and Norford (1967) as the products of solution collapse. Similar breccias in the study area were also attributed to solution collapse (Mott, 1989; McMechan and Leech, 2011).

Breccias containing dolostone fragments, but of uncertain origin, coincide with the main mineralized REE-fluorite zone (see below). The elongate shape of the breccia zone suggests that it may be either a fault related ('crackle fault breccia') or a 'cave-ceiling crackle breccia' related to stratabound paleokarst development. Regardless of its origin, this breccia appears to be the main structural control on REE-fluorite mineralization, and for pyrite and sparry dolomite mineral growth.

4. Geology of the deposit

REE-fluorite mineralization coincides with a zone of dolostone-fragment crackle breccia hosted by the Cedared and Burnais formations (Figs. 2, 3). Fluorite-bearing outcrops extend across an area 3300 metres long and 750 metres wide. The main mineralized zone is approximately 50 metres from, and parallel to, the contact between the Cedared and Burnais

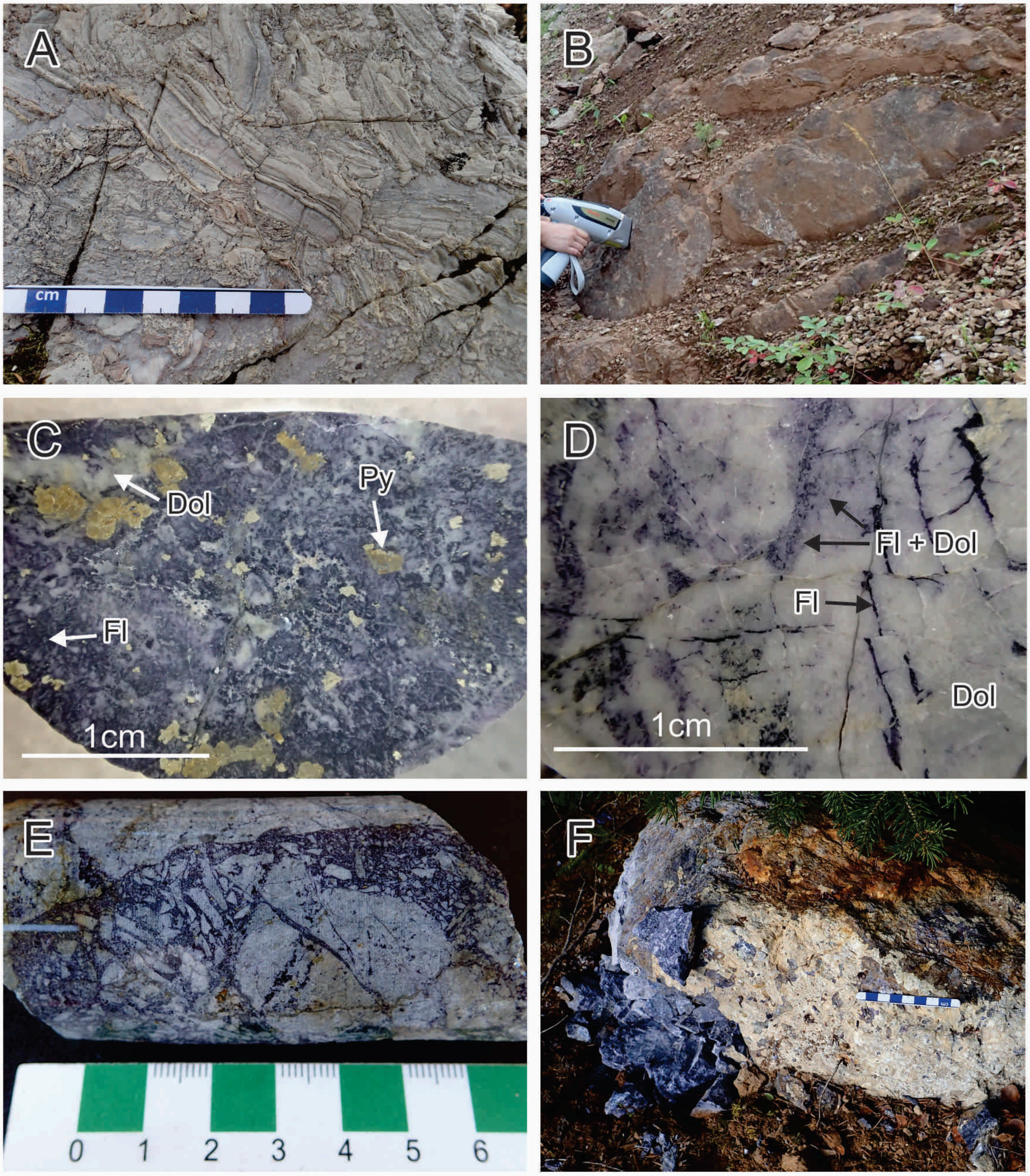

Fig. 4. Photographs from the Rock Canyon Creek deposit area. **a)** Intraformational breccia composed of evaporitic laminated gypsum of the Cedared and Burnais formations, weathered surface. **b)** REE-fluorite-bearing dolostone, the main zone, displaying characteristic red-brown weathering. **c)** Representative sample of mineralization consisting of purple fluorite (Fl) and pyrite (Py) in grey dolomite (Dol). REE-bearing minerals cannot be identified at this scale; however sample contains 1.8 weight % of Ce, La, and Nd combined. **d)** Example of 'crackle breccia' cemented by fluorite in the right portion of the photograph; open spaces filled by fluorite and dolomite (Fl + Dol). **e)** Monolithic dolostone breccia; larger fragments are cut by fluorite filled fractures; purple matrix of the breccia consists of fluorite, dolomite, barite, and pyrite. **f)** Fluorite-rich boulder suspected to contain cryolite found near the northwestern end of the main REE-fluorite zone.

formations and the Maligne Formation (Figs. 2, 3). Defined by drilling and illustrated in cross-section (Pighin, 2010), the zone appears to dip steeply along a strike length of more than 1100 metres, and appears to be stratabound, subparallel to the contact of the Cedared and Burnais formations with the overlying Maligne Formation. Mineralization was intersected to a depth of 124 metres; remains open at depth and along strike, and may be more than 50 metres thick. Based on fluorine concentrations reported by Pighin (2010) and assuming that most of the fluorine is contained in fluorite, we estimate that fluorite content varies from less than 1% to 13.5% by weight. Most of the fluorite is deep purple, although, red-wine coloured and colourless varieties were also observed. The main mineralized zone displays significant concentrations of REE. Light REE (Ce+La+Nd) concentrations vary from trace to 2.8% (Pighin, 2010). Spectrum Mining Corporation did not analyse for rare earth elements other than Ce, La, Nd, and Sm.

The main mineralized zone is dark red-brown on weathered surfaces (Fig. 4b), and grey and purple on fresh surfaces (Fig. 4c). Fluorite mineralization in the main zone is fracture controlled and as open space fillings (Fig. 4d). Early disseminated mineralization was reported in previous studies (Samson et al., 2001; Gagnon et al., 2003). Recent field observations suggest that disseminated fluorite forms envelopes around fluorite-filled fractures and breccia zones (Fig. 4e). The deepest purple fluorite appears to form haloes around radioactive grains (possibly monazite). Fluorite-filled hairline fractures cut the dolostone and dolostone breccia fragments. Coarser fractures (up to 1 cm thick) are commonly filled with fluorite (±carbonate and pyrite). Cross cutting relationships, symmetrically banded complex fracture fillings, and oscillatory growths in fluorite suggest multiple generations of fluid flow and fluid evolution with time. Based on a comparison of REE and fluorine content of analyzed drill core as reported by Pighin (2010), REE mineralization is spatially associated with fluorite. However, specific REE minerals are too fine grained to be identified macroscopically. Several generations of pyrite are in the mineralized zone. Pyrite occurs as cubes and pyritohedrons in aggregates and veinlets, and fine pyrite veinlets crosscut fluorite mineralization. The REE, fluorite, and pyrite content of other fluorite occurrences, which are hosted by white to pale gray carbonate, is significantly lower than that of the main REE-fluorite zone.

The mineralogy of the deposit (Table 1) was described by Hora and Kwong (1986), Pell (1992), Kerr (1995), Zhu (2000), and Samson et al. (2001). The studies by Hora and Kwong (1986) were largely based on samples of float. Pell (1992) complemented the data by describing some in-situ mineralization. Studies by Samson et al. (2001), Kerr (1995), and Zhu (2000) described both in-situ and float mineralization. Calcite, dolomite, fluorite, quartz, K-feldspar, barite, apatite (decomposed apatite), pyrite, REE carbonates [bastnaesite-(Ce), parisite-(Ce), synchysite-(Ce)], and a mixture of REE phosphates including monazite-(Ce) were identified by Hoshino et al. (2017). Rare earth element mineralization occurs with hydrothermal stage fluorite and barite, and is crosscut by later-stage calcite veinlets (Hoshino et al., 2017). More detailed mineralogical studies on the drill core samples of the main REE-fluorite zone are in progress and will establish a paragenesis.

Cryolite, prosopite, and elpasolite have been observed in rounded and sub-rounded float boulders near the deposit (Fig. 4f). However, these minerals have not been found in samples collected from outcrops and drill core. These boulders may either indicate undiscovered mineralization on the property, or they may have been derived from as far as the Ice River complex and transported by glaciation. The second explanation is less likely because Spectrum Mining Corporation failed to locate boulders with similar characteristics in drainages north of Rock Canyon Creek and south of the Ice River complex.

5. Genetic considerations and possible genetic link to magnesite and MVT deposits in southeastern British Columbia

The Rock Canyon Creek REE-fluorite deposit has historically been viewed as a being related to a carbonatite source (Graf, 1985; Hora and Kwong, 1986; Pell and Hora, 1987; Samson et al., 2001). Disseminated fluorite–REE mineralization was regarded as a result of interaction between F- and REE-bearing hydrothermal fluids of unspecified origin with carbonate wall rock (Gagnon et al., 2003). Differences in fluorite composition were interpreted either as progressive mixing of hydrothermal fluids or interaction of fluids with the country rock (Gagnon et al., 2003).

Although the deposit is in the British Columbia alkaline province (Pell, 1994), it is unusual in that it is not spatially associated with outcrops of carbonatite or alkaline rocks. Furthermore, it lacks primary monazite, although secondary monazite was recently reported in shallow drill core by Hoshino et al. (2017) from drill hole number RCC-09-14. Similarities between the Rock Canyon Creek REE-fluorite deposit, Mississippi Valley-type (MVT; e.g., Shag, Monarch, Kicking Horse, Munroe), and sparry magnesite deposits (e.g., Mount Brussilof Mine and related occurrences) in southeastern British Columbia were noted by Paradis and Simandl, in press. All the above deposits are in Paleozoic shelf carbonate rocks, which extend along the length of the Canadian Cordillera, and were likely generated by mineralizing processes operating in the absence of nearby magmatic sources of metals and heat. All of these deposit types are associated with breccias and zones of hydrothermal sparry carbonates, such as magnesite, calcite, and saddle dolomite, and contain sulphides (Paradis and Simandl, in press). Furthermore, Pell (1994) reported that the Rock Canyon Creek deposit was discovered as a result of geochemical exploration for MVT Zn-Pb deposits. Thus basinal fluids may have been responsible for, or at least partially contributed to, the formation of REE-fluorite mineralization at Rock Canyon Creek

Possible links between the MVT and magnesite deposits and Rock Canyon Creek will be tested by future studies directed at establishing lithological, textural, mineralogical

Table 1. Mineralogy of the Rock Canyon Creek deposit. Sources: 1 - Hora and Kwong (1986), 2 - Pell (1992), 3 - Samson et al. (2001), and 4 - Hoshino et al. (2017).

		Mineral	**Formula**	**Sources**
In-situ	**Gangue**	Calcite	$CaCO_3$	4
		Dolomite	$CaMg(CO_3)_2$	3,4
		Ferroan Dolomite	$CaMg(CO_3)_2$	3
		Pyrite	FeS_2	2,4
		K-Feldspar	$KAlSi_3O_8$	3,4
		Quartz	SiO_2	3,4
		Rutile	TiO_2	3
		Magnetite	$Fe^{2+}Fe^{3+}{}_2O_4$	2
		Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	3,4
		Hematite	Fe_2O_3	3,4
	Ore	Fluorite	CaF_2	2,3,4
		Barite	$BaSO_4$	2,3,4
		Bastnaesite	$(Ce,La,Y)CO_3F$	4
		Pyroclore	$(Na,Ca)_2Nb_2O_6(OH,F)$	3
		Parisite	$Ca(Ce,La)_2(CO_3)_3F_2$	2,3,4
		Synchysite	$CaCe(CO_3)_2F$	3,4
		Monazite	$(Ce,La)PO_4$	4
		Sphalerite	$(Zn,Fe)S$	3
		Galena	PbS	3
		Cerussite	$PbCO_3$	3
		Smithsonite	$ZnCO_3$	3
In-situ & Float	**Gangue**	Dolomite	$CaMg(CO_3)_2$	1,3,4
		Pyrite	FeS_2	1,2,4
		K-Feldspar	$KAlSi_3O_8$	1,3,4
		Quartz	SiO_2	1,3,4
		Rutile	TiO_2	1,3
	Ore	Bastnaesite	$(Ce,La,Y)CO_3F$	1
		Fluorite	CaF_2	1,2,3,4
		Barite	$BaSO_4$	1,2,3,4
Float	**Gangue**	Limonite	$FeO(OH)\cdot nH_2O$	1
		Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$	1
		Prosopite	$CaAl_2(F,OH)_8$	1,3
		Kaolinite	$Al_2Si_2O_5(OH)_4$	1,3
		Talc	$Mg_3Si_4O_{10}(OH)_2$	1
		Muscovite	$KAl_2(AlSi_3O_{10})(F,OH)_2$	3
		Elpasolite	K_2NaAlF_6	3
		Goyazite	$SrAl_3(PO_4)(PO_3OH)(OH)_6$	3
	Ore	Gorceixite	$BaAl_3(PO_4)(PO_3OH)(OH)_6$	1
		Cryolite	$Na_3{\bullet}AlF_6$	3
		Ag-Sn-Te-S phase	$Ag_8Sn(TeS_2)_2$	3

and geochemical parameters, depositional conditions, mineralization ages, provenance of metals and sulphur, tectonic and structural controls, and variations in the C and O isotopes in carbonate rocks. Conceivably, Rock Canyon Creek mineralization may record interaction between carbonatite-related and basinal fluid mineralizing systems.

6. Ongoing and future work

Samples collected in 2016 are being analysed for major and trace elements including REE and fluorine and mineralogical studies are in progress. Our future work, focused on generating a dataset to enable comparisons with magnesite and MVT deposits in the area, includes the following.

- Fieldwork to determine the extent of the brecciated and mineralized zones, document changes in brecciation style, and establish the distribution and intensity of sparry dolomitization adjacent to the main mineralized zone.
- Developing a three dimensional model of the deposit based on geochemical analyses of core samples.
- Detailed petrography and mineral chemistry using the scanning electron microscope (SEM) and electron microprobe.
- LA-ICPMS studies for trace element analysis and fluid inclusion studies of fluorite to test for covariation in REE composition of fluorite, and temperature of the fluid.
- S-isotopes of sulphides and barite, and O, C and Sr isotopes of carbonate rocks.
- Re-Os (pyrite) and U-Pb (monazite) geochronology.
- Study of co-variation between fluorite, sulphur, major and trace elements relative to concentrations of REE.
- Comparison of REE normalized patterns of weathering-enriched mineralization relative to those corresponding to fresh mineralization.

Acknowledgments

This study is part of the Targeted Geoscience Initiative 5, spearheaded by Natural Resources Canada, and in partnership with the Japan Geological Survey. We thank David Pighin for his perspectives on the geology of the district and for allowing us access to drill cores stored at the Vine property south of Cranbrook. We are grateful for improvements and suggestions of Dr. Margot McMechan of the Geological Survey of Canada in Calgary and JoAnne Nelson, British Columbia Geological Survey.

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