

# Carbonatite-Associated Rare-Earth-Element Mineralization in the Eastern Part of the Ice River Carbonatite Complex, Southeastern British Columbia (NTS 082N/01)

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## Introduction

Carbonatites are mantle-derived, silica-poor igneous rocks with >50 vol. % primary carbonate minerals (Yaxley et al., 2021). Despite being silica-poor, the modal ratio of carbonate to silicate minerals is highly variable in carbonatites (Christy et al., 2021) and is dependent on how their parental magma is generated and evolves before emplacement. Carbonatites are of significant interest to exploration companies due to their high concentrations of rare-earth elements (REEs). As carbonatite magma evolves, REEs and other incompatible elements concentrate within residual melts (Anenburg et al., 2021). Anorogenic, rift-related settings facilitate the emplacement of small-volume magmas produced by decompressional melting of the underlying mantle. This allows the emplacement of alkali-rich, silicaundersaturated magmas (which can crystallize and form rocks such as carbonatite, nephelinite and phonolite) within large-scale, intraplate extensional structures (Chakhmouradian and Zaitsev, 2012). Examples of such anorogenic alkaline rock-carbonatite igneous provinces include the Kola Peninsula of Russia and the East African Rift system. Carbonatites and alkaline rocks in orogenic settings may also host concentrated REEs (Song et al., 2016). In orogenic settings, carbonatite emplacement occurs either during postorogenic collapse or before a transition from a convergent to divergent tectonic setting (Yaxley et al., 2022). The cooling and crystallization of carbonatite magmas are accompanied by the release of alkali-rich fluids, which metasomatically alter (fenitize) surrounding country rocks (Le Bas, 2008). Fluids derived from carbonatite magmas contain elevated levels of alkalis and volatiles, which can transport incompatible elements like REEs (Elliott et al., 2018). Therefore, metasomatically altered rocks (fenites) can in principle provide information on the magmas from which the fluids were sourced and any associated mineral deposits.

To form economic concentrations of REEs in igneous rocks, some sort of evolutionary process (liquid immiscibility, fractional crystallization or the release of fluids from magma) is required (Chakhmouradian and Zaitsev, 2012). Furthermore, carbonatites are often affected by hydrothermal fluids, which facilitate the development of late-stage REE mineralization. The interaction of primary magmatic REE-bearing minerals (e.g., burbankite and carbocernaite) with carbonate-, chloride-, fluoride- or phosphate-rich hydrothermal fluids enables their dissolution and precipitation of secondary REE phases (Williams-Jones et al., 2012; Anenburg et al., 2021). The presence of fenitized rocks and REE-bearing minerals, such as bastnäsite, parisite, synchysite, Ba-REE fluorocarbonate and monazite, indicate REE enrichment due to hydrothermal interaction (Wall et al., 2008; Chakhmouradian and Wall, 2012; Hoshino et al., 2016). As with hydrothermal dissolution-reprecipitation, weathering can also be responsible for the breakdown of primary REE phases allowing the transport of REEs into later formed REE phases (Anenburg et al., 2021). Because carbonatites are susceptible to subsolidus re-equilibration (Chakhmouradian et al., 2016), understanding how the mineralogy of a given carbonatite has been affected by postmagmatic processes is critical for determining its mineralization potential.

## **Ice River Complex**

The lead author's graduate research is focused on a carbonatite-associated REE exploration prospect in the eastern aspect of the Ice River Complex (IRC). The prospect is located 42 km southeast of Golden, in the British Columbian portion of the Vermillion Range, where it is sandwiched between, and bordered by, Yoho and Kootenay National parks. Since 2003, Eagle Plains Resources has been conducting exploration on the property. TerraLogic Exploration Inc. (on behalf of Eagle Plains Resources) ran six exploration projects (in 2006–2010 and 2012) to ad-

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vance their understanding of the bedrock geology of the IRC within its contact aureole (Brown and Holowath, 2022). The IRC is a late Devonian to early Carboniferous alkaline intrusion, which has a J-like outline in plan view and measures approximately 18 km in length and 29 km<sup>2</sup> in total exposure. A geological map and description of the complex are provided in Figure 1. Weakly metasomatized Cambrian and Ordovician limestone, dolomite and shale country rocks (Chancellor and Ottertail formations and McKay Group) host the intrusion. The oldest parts of the intrusion (hereafter referred to as the layered series) comprise a rhythmically stratified, feldspar-poor, ultramafic to mafic series ranging in modal composition from jacupirangite to urtite. The layered series is crosscut by feldspathoid syenites (hereafter referred to as the syenite series) and carbonatite, which are in turn crosscut by lamprophyre dikes (Locock, 1994; Peterson and Currie, 1994; Mumford, 2009; Brown and Holowath, 2022). Emplacement of the IRC is believed to have resulted in the formation of a contact metasomatic skarn at the margins of the complex (Currie, 1975).

During the Laramide orogeny, the IRC and surrounding hostrocks were thrust approximately 200 km to the east, along a west-dipping décollement surface (Gabrielse, 1991). The IRC behaved as a relatively competent mass during transport, whereas the surrounding hostrocks were strongly sheared (Locock, 1994). Marginal units of the IRC show strong deformation (e.g., gneissosity and boudinage; Mumford, 2009). Both the IRC and hostrocks were affected by regional metamorphism of prehnite-pumpellyite facies with pressures of 2–9 kbar and temperatures of 200–400 °C (Currie, 1975; Locock, 1994). Gabrielse (1991) suggested that regional metamorphism was coeval with the eastward thrusting of the IRC. There is a large diversity of carbonatite types in the IRC, differing in petrography and structural characteristics. The following description is a summary of previous work on these rocks. Carbonatites occur as dikes and plugs, intruding alkaline igneous, silicate igneous and metasedimentary hostrocks (Currie, 1975; Peterson and Currie, 1994). The carbonatites vary in colour from white to almost black. Currie (1975) identified three carbonatite bodies within the IRC. The largest one is a lenticular plug (400 by 1500 m) of white- to buff-weathering calcite carbonatite (unit 10, Figure 1) containing minor aegirineaugite, fluorapatite and phlogopite and accessory pyrochlore, pyrite, strontianite and ilmenite. This largest carbonatite body is visible east of Aquila Mountain on Figure 1. Calcite-carbonatite dikes (thin, elongate bodies of unit 10, Figure 1) commonly intrude the layered series (units 5–9, Figure 1) and the syenite series (units 11–15, Figure 1; Pell, 1987). Associated with the large calcitecarbonatite body are black-weathering dikes with major calcite, siderite and berthierine; also present are minor biotite, aegirine, edingtonite, perovskite and ilmenite, as well

as trace quantities of sphalerite and pyrite (Locock, 1994). A younger red-weathering carbonatite is mineralogically similar to the black-weathering carbonatite, but contains up to 10 vol. % noncarbonate minerals, including serpentine, pyrochlore and xenotime (Pell, 1987). In addition, carbonatites with ropy textures, possibly indicating ductile deformation, were reported by Currie (1975). More silicarich, massive, dark green carbonatites have also been documented, but no detailed information on their mineralogy is currently available.

In the eastern part of the IRC (the Moose Creek valley [MCV], outlined in purple in Figure 1), the carbonatites have complex, poorly understood structural and temporal relationships to the syenites (Mumford, 2009); carbonatite and syenite bodies locally crosscut each other. This ambiguous structural relationship may be due to multiple phases of carbonatite emplacement (Pell, 1987). It has also been proposed that syenite-associated carbonatites are related to the red-weathering carbonatite described above (Peterson, 1983). Syenite-associated carbonatites are distinct due to low abundances of silicate minerals in these rocks, and the presence of ankerite, barytocalcite and strontianite in addition to calcite (Peterson, 1983; Pell, 1987). Associated silicate minerals in syenite-associated carbonatites include phlogopite, alkali feldspars (dominantly albite with minor microcline) and zeolites (natrolite, analcime and minor edingtonite; Pell, 1987). Whole-rock geochemical analyses of the carbonatites show variable Nb and REE contents (Pell, 1987). The syenites are relatively more enriched in Nb, but relatively less enriched in REE in comparison with the carbonatites (Brown, 2013).

The aims of this study are to 1) describe the mineralogy and paragenetic characteristics of the different carbonatites in the MCV, with an emphasis on REE-bearing phases and 2) identify distinct mineralization styles, which correlate to geochemical variations and anomalies in the hostrocks. Using new analytical data, an attempt will be made to constrain the source of REE mineralization in the eastern part of the IRC and identify the relationships between mineralization styles and carbonatite interaction with their hostrocks.

## Methodology

Identification of paragenetic sequences is fundamental in understanding the REE-mineralization styles in the IRC and has implications for the petrogenesis of the complex. For this study, there is a particular emphasis on the identification of REE-bearing minerals and the processes that have led to their formation. An in-depth understanding of their compositional and paragenetic characteristics is essential to determining the economic potential of the IRC. For this purpose, 57 rock samples were collected during the 2022 field program. Sample sites were selected based on field



**Figure 1.** Geology of the Ice River Complex (IRC) showing the major units in the complex. The study area (the extent of Eagle Plains Resources' [EPL] tenure) is shown as a black outline along the eastern margin of the complex. The area of the Moose Creek valley (MCV), as considered for this study, is outlined in purple. The original field mapping was undertaken by Currie (1975), later digitized by TerraLogic Exploration Inc. Geological data from Cui et al. (2017) has been added. BC MINFILE entries: Moose Creek, MINFILE 082N 027; Shining Beauty, MINFILE 082N 025; Waterloo, MINFILE 082N 028; Yippie, MINFILE 082N 097; Zinc Creek, MINFILE 082N 026 (Brown and Holowath, 2022; BC Geological Survey, 2024). All co-ordinates are in UTM Zone 11N, NAD 83. Legend on the following page.

Age	Subgroup	Map unit	Key	Unit description (modified from Currie, 1975)
Quaternary		Unconsolidated sediments	17	Glacial sediments, fluvial sediments, talus rock flour and related materials
Ice River Alkaline Complex units				
Devonian or Carboniferous		Lamprophyre (minette and sannaite)	16	Melanocratic rocks occasionally ocellar, with phenocrysts of pyroxene and kaersutite, sometimes in a feldspar-bearing matrix
Devonian or Carboniferous	Syenite series	Altered zeolite-rich syenite	15	Buff-weathering rocks rich in secondary natrolite with minor carbonate and aegirine
		Sodalite-nepheline syenite	14	Massive to faintly gneissic leucocratic green to blue rocks, including veins and dikes
		Leucocratic nepheline syenite	13	Pale greenish, distinctly gneissic rock commonly bearing kaersutite and sodalite
		Meso- to melanocratic syenite	12	Migmatite and agmatite gneiss
		Silica-saturated contact breccia	11	Pale, fine-grained hybrid rocks, commonly saturated, with metasediment blocks, includes minor amounts of units 12, 13
Devonian or Carboniferous	Carbonatite	Buff-weathering carbonatite	10	White to buff, foliated carbonate and massive, altered, melanocratic silicocarbonatite
Devonian or Carboniferous	Layered series	Urtite	9	Coarse-grained to pegmatitic pale green rocks
		Ijolite	8	Medium- to coarse-grained bluish rocks with cubic nepheline set in euhedral pyroxene lathes
		Titaniferous andradite ijolite	7	Medium- to coarse-grained brownish-black rocks with cubic nepheline, vitreous brown garnet
		Mela-ijolite	6	Coarse-grained blue-black rocks with prominent biotite phenocrysts and clumps
		Jacupirangite	5	Black to greenish pyroxenite with small cubes of nepheline, and minor biotite
		Ice River Alkaline Compl	ex ho	strock units
Devonian or Carboniferous		Contact skarn	4	Banded skarn and calcsilicate rocks, contact- altered sedimentary rocks formed during emplacement of the complex
Cambrian to Ordovician		McKay Group	3	Limy shales with interbanded thin limestones generally grey-green with local brownish stripings and dolomite layers
Cambrian		Ottertail Formation	2	Massive grey-blue limestone, shaly horizons toward the base and top
		Chancellor Formation	1	Reddish slaty shale, commonly thinly fissile, minor limy horizons and dolomite

Figure 1 (continued). Legend for geology of the Ice River Complex, showing the major units in the complex.



observations and the results of a scintillometer-assisted survey (Brown and Holowath, 2022), which targeted anomalies outlined in Brown (2013). From this sample suite, a total of 35 polished thin sections were prepared from selected samples chosen on the basis of whole-rock geochemical data (major- and trace-element concentrations), using such geochemical indicators as total REE, Ba, Zr, Nb, Th, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> contents. The incompatible trace elements were chosen for their association with mantle-derived magmatism and generally low levels in metasedimentary hostrocks, whereas the SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> values are useful for discriminating between carbonatites, alkaline silicate rocks and their metasomatically modified variants.

The polished thin sections were examined using a Leica Microsystems Leica DM750 P polarizing microscope to identify major constituent minerals and textural characteristics. The sections were then examined using a variety of analytical techniques, including cathodoluminescence (CL) and backscattered-electron (BSE) imaging, energy dispersive X-ray spectrometry (EDX) and wavelength-dispersive X-ray fluorescence (WDXRF), and Raman vibrational microspectroscopy (Raman). By using a combination of imaging and quantitative techniques, a comprehensive understanding of textural (BSE and CL) and compositional (EDX, WDXRF, Raman) characteristics of the selected sample suite was achieved.

Cold-cathode CL imaging is used for luminescent minerals (such as calcite, apatite and fluorite; Mitchell et al., 2017) to identify trace-element-induced compositional variations and zonation, which would be undetectable in BSE images, including variations arising from REE substitutions in these minerals. In tandem with CL imaging and EDX, BSE imaging was used to elucidate interrelations among different minerals, and in particular, microtextural characteristics beyond the resolution of an optical microscope (such as exsolution lamellae and symplectic intergrowths). Optical, CL and BSE imaging were also used to identify and map representative areas of interest for further quantitative analysis.

Quantitative microbeam techniques enable major- and trace-element compositional variations to be determined in situ and with a spatial resolution of 10–30 m. A nondestructive microbeam technique capable of detecting major and minor elements in mineral grains at concentrations >200 ppm is WDXRF. For accurate petrographic characterization of all rock types in this study, WDXRF was used to determine the major-element composition of all constituent minerals (feldspars, clinopyroxenes, calcite, etc.) and REE phases. Raman was used to identify polymorphs and compositionally similar phases that cannot be reliably discriminated using a combination of EDX and CL imaging. To enable accurate beam positioning, matching BSE and reflected-light microscopic images and maps of target areas were used.

#### **Moose Creek Valley**

#### Structure

Igneous rock exposures in the MCV are abundant at higher elevations in the western flank of the valley, where they are hosted within the Ottertail Formation and McKay Group. Igneous rock exposures in the MCV generally dip gently westward. Throughout the MCV, three phases of deformation are recognized. Folding F<sub>1</sub> is characterized by smallscale, tight folds around the margins of the syenite series. This deformation event was probably caused by syenite emplacement. Folding F2 represents a structurally dominant compressive event caused by the Laramide orogeny, and is characterized by open, north- to northwest-trending axial traces. In the MCV, the main exposure of  $F_2$  is a sigmoidal-shaped, open- to isoclinal-plunging anticline, which trends north-northwest to west-northwest. Postorogenic dextral shear rotated the jacupirangite-urtite layered series, carbonatite plug and surrounding hostrock  $\sim 30^{\circ}$  and is also responsible for the sigmoidal shape of the F<sub>2</sub> anticline and local tertiary folding (F<sub>3</sub>; Currie, 1975).

## Late-Stage Igneous Features of the MCV

Numerous syenite, lamprophyre and carbonatite dikes and sills are exposed within the MCV. Three distinct groups of intrusions were identified: 1) a nepheline syenite-nephelinolite group, 2) a syenite-monzodiorite group and 3) an alkali feldspar granite dike. The syenite dikes are typically grey, follow a north-northwest trend, and dip between 35° and 65° (Figure 2a; Mumford, 2009). Their texture is fine grained to pegmatitic and commonly inequigranular; individual bodies range from 0.20 m to several metres in width and may be traced in outcrop for ~200 m. Syenite bodies, which intrude the Ottertail Formation, generally conform to bedding in the hostrock and, therefore, can be classified as sills. Syenite intrusions are strongly deformed, which is observed as boudinage at the outcrop scale and as foliated biotite aggregates at the thin-section scale (Mumford, 2009).

Another abundant igneous rock type in the MCV is lamprophyre. It occurs as dark grey to dark green dikes ranging from 0.15 to 5 m in width. The dikes crosscut both the IRC and surrounding metasedimentary sequence, follow a northwest trend and have similar dips to the syenite intrusions (Figure 2b). Two principal varieties of lamprophyre have been identified: aphanitic to fine-grained, amphibolerich sannaite and conspicuously porphyritic, biotite-rich minette. The lamprophyres are locally deformed, as indicated by calcite-filled tension gashes and boudinage. Mumford (2009) noted isotopically indistinguishable syenite-lamprophyre dike assemblages occurring throughout





**Figure 2.** Photographs of late-stage igneous features in the Moose Creek valley, southeastern British Columbia: **a**) ridge between Buttress Peak and Manganese Mountain (looking south) showing syenite dikes emanating from the syenite series into surrounding Ottertail Formation limestone (unit 2, Figure 1); **b**) minette dike (outlined with yellow dashed line) on the ridgeline between Sentry Peak and Zinc Mountain (looking south) intruding meso- to melanocratic syenite (unit 12, Figure 1); **c**) carbonatite dike crosscutting carbonate metasedimentary rocks south of the ridge between Manganese Mountain and Buttress Peak (note F<sub>3</sub> folding in the hostrock).

the MCV, and presumably they were derived from the same source as the lamprophyres. Both lamprophyre and syenite intrusions exhibit a similar orientation with respect to the regional tectonic fabric, indicating their postemplacement rotation into the main foliation plane ( $S_3$ ; Figure 2c).

# Carbonatite Field Relationships

The least abundant intrusive rock in the MCV (both in volume and number of mapped bodies) is carbonatite. This rock is typically found as sills or dikes measuring from 0.10 to 2 m in width. However, numerous thinner crosscutting veins and veinlets comprising similar mineral assemblages are also observed in the syenites and metasedimentary hostrocks (Figure 3a-c). For this study, large carbonatite bodies and pervasively metasomatized rocks were preferentially sampled because they can be more readily recognized in the field based on their distinctive structural characteristics (such as crosscutting relationships or recessed units). Also, a scintillometer-assisted survey in the MCV showed the radiometric response from the carbonatites was low but greater than the hostrock background (Brown and Holowath, 2022). Areas of elevated radiometric response were targeted for sampling. The sampled intrusions are moderately to steeply dipping (24-90) bodies that generally follow a south-southwest trend and range from 2 to >50 m in exposed length.

Three varieties of carbonatite were identified on the basis of field, geochemical and petrographic characteristics: pale greyish dolomite carbonatite; white to light grey, saccharoidal, calcite carbonatite; and cream to pink, barytocalcite carbonatite. Oxidized carbonatite varieties are orangebrown to dark brown owing to the replacement of accessory pyrite by Fe-oxyhydroxides. Potentially related to the barytocalcite carbonatite is a fracture-hosted hydrothermal carbonate-rich assemblage observed in both calcite carbonatites and syenites. The texture of carbonatites ranges from fine to coarse grained and from subequigranular to brecciated. All samples show some textural evidence of postemplacement ductile and brittle deformation.

# Mineralogy of the Eastern Ice River Complex Carbonatites

# Dolomite Carbonatite

Dolomite carbonatite is interpreted to be the earliest phase of carbonatite magmatism in the eastern IRC, where it is confined to the area surrounding the Yippie mineral showing (MINFILE 082N 097, BC Geological Survey, 2024; Figure 1). Of particular note in this area is an anastomosing carbonatite-syenite sill (Figure 3a) associated with the greatest REE enrichment recorded on the property (Brown and Holowath, 2022). This carbonatite is composed predominantly of mosaic-textured, fine- to medium-grained dolomite (Figure 4a). Its most notable petrographic feature





Figure 3. Photographs of carbonatite dikes in the Moose Creek valley (MCV), southeastern British Columbia: a) carbonatite–syenite sill at the Yippie showing (MINFILE 082N 097, BC Geological Survey, 2024), associated with the greatest rare-earth-element enrichment within the study area; b) brown, oxidized, calcite carbonate dike, viewed looking northward toward Sentry Peak; c) white, calcite carbonatite breccia crosscutting the McKay Group, southeast of Mount Mollison.



**Figure 4.** Images of dolomite and calcite carbonatites, Ice River Complex, southeastern British Columbia: **a**) backscattered-electron (BSE) image of dolomite (Dol) carbonatite intruded by calcite (Cal) carbonatite; **b**) BSE image of relict accessory monazite (Mnz) surrounded by a poikilitic reaction rim comprising fluorapatite (Fap), ancylite (Anc) and strontianite (Str); **c**) cathodoluminescence image of b) and surrounding area showing yellow-luminescing calcite crosscutting dolomite and blue luminescing fluorapatite rims on nonluminescent monazite. Abbreviations: Bbn, burbankite; BCal, barytocalcite; Ca, calcium; Sr, strontium.



is accessory equant monazite, which is partially replaced by secondary REE-Sr-Ba phases (Figure 4b, c).

# Calcite Carbonatite

The most common variety of carbonatite found throughout the MCV is calcite carbonatite. The best-studied example is a dike composed predominantly of mosaic-textured, fineto coarse-grained calcite, minor platy phlogopite and fibrous magnesioarfvedsonite near fenitized contacts. Toward the rim, there is a decrease in Mg content in calcite grains, which indicates their crystallization from an initially Mg-rich source (Viladkar, 2000; Chakhmouradian et al., 2016). Phlogopite crystals are also zoned and characterized by Mg enrichment in their cores relative to more Ferich rims (Figure 5a). Accessory phases include monazite and burbankite, which occur as ovoid inclusions encapsulated in calcite, pyrrhotite or sphalerite (Figure 5b). Monazite and burbankite appear to have reacted with postmagmatic fluids (evidenced by the precipitation of hydrous minerals), producing reaction rims or pseudomorphs composed of ancylite, apatite, strontianite, barite and calcite (Figures 4b, c, 5c). Silicate-rich varieties of calcite carbonatite containing elevated levels of SiO<sub>2</sub>, K<sub>2</sub>O, FeO and MgO contents are typically weathered to an orange-brown colour owing to oxidation of ferromagnesian silicates (in particular, replacement of biotite by chamosite and, to a lesser extent, clinochlore). Throughout the MCV, silicaterich calcite carbonatite is more abundant than silicate-poor calcite carbonatite and contains brecciated fragments of the country rocks (Figure 5d).

## Barytocalcite Carbonatite

A vein of cream to pink barytocalcite carbonatite with a glimmerite contact margin was observed at the intersection between jacupirangite and melasyenite units. Its association with glimmerite indicates contact-metasomatic changes similar to those reported for other carbonatites in British Columbia (Chakhmouradian et al., 2015; Rukhlov et al., 2018). Barytocalcite carbonatite is a newly recognized rock type for the IRC, making it one of just a few localities worldwide where barytocalcite has a rock-forming status (Zaitsev et al., 1998; Reguir, 2001). Whole-rock geochemical analysis of the sample collected from this carbonatite shows anomalously high concentrations of Ba, Sr and REE (~12.5, 1.9 and 1.4 wt. %, respectively). Fine- to

Figure 5. Images of calcite carbonatite assemblages, Ice River Complex, southeastern British Columbia: a) backscattered-electron (BSE) image of zoned phlogopite (PhI) in calcite (Cal) carbonatite; b) BSE image of ovoid monazite (Mnz) and titanium-rich magnetite (Ti Mag) inclusions in pyrrhotite (Po); c) BSE image of a pseudomorph after burbankite composed of ancylite (Anc), strontianite (Str), apatite (Ap), barite (Brt) and partially resorbed dolomite (Dol); d) crossed-polarized light image of comb-textured calcite carbonatite containing xenoliths of foliated McKay Group metasedimentary rock. Abbreviation: Gn, galena.







Figure 6. Images of barytocalcite carbonatite vein, Ice River Complex, southeastern British Columbia: a) cathodoluminescence image of barytocalcite (BCal) showing trace-element zoning, which is undetectable optically; note red-luminescing calcite (Cal) near the glimmerite-barytocalcite vein contact; b) corresponding plane-polarized light image of the barytocalcite vein and glimmerite composed of phlogopite (PhI) and ilmenite (IIm).

medium-grained barytocalcite makes up the bulk of this vein and is also developed interstitially within the glimmerite (Figure 6a, b). The remainder of the vein is composed of accessory strontianite and ancylite, which are found as very fine-grained overgrowths on incorporated barite and ilmenite grains. In CL images, barytocalcite luminesces dull to bright yellow; smaller patches of red-luminescing calcite are found within the glimmerite and at its contact with barytocalcite (Figure 6a).

# Hydrothermal Carbonate Assemblages

Mineralogically complex hydrothermal carbonate assemblages are hosted in thin veinlets crosscutting syenites (Figure 7a) and carbonatites (Figure 7b, c). These assemblages share many similarities with the barytocalcite carbonatite, in particular, an abundance of Ba and Sr carbonate phases. The principal difference between the assemblages and the barytocalcite carbonatite is the abundance of chlorite (dominantly chamosite) in the former. The instability of biotite, paucity of hematite and abundance of chamosite, il-



Figure 7. Images of veinlet-hosted hydrothermal carbonate assemblages, Ice River Complex, southeastern British Columbia: a) backscattered-electron (BSE) image of fracture infill of barytocalcite (BCal), strontianite (Str), ancylite (Anc) and thorite (Thr) in K-feldspar (Kfs)-rich syenite with minor biotite (Bt); in syenites, smaller-scale fractures are composed of thorite 'rims' surrounding fracture edges, strontianite and ancylite 'blockages' in fluid pathways, and barytocalcite forming around the strontianite-ancylite blockages; b) BSE image of fracture infill of alstonite (Asn), ancylite, strontianite and thorite in carbonatite; in comparison with a), there is more ancylite and less thorite in this assemblage; the alstonite present in this assemblage is a polymorph of barytocalcite; the fracture infill in carbonatites is distinctly less ordered, compared to a); c) cathodoluminescence image of zoned apatite (Ap) occurring close to the hydrothermal assemblage shown in b); wavelength-dispersive X-ray fluorescence analysis of the apatite indicates light rareearth-element enrichment in blue-luminescing zones. Abbreviation: Cal, calcite.



menite and locally siderite in this hydrothermal assemblage imply acidic conditions conducive to  $K^+$  and  $Fe^{2+}$  mobility (Mücke, 2005; Chakhmouradian et al., 2015). The fractureinfilling material is very fine grained and typically comprises alstonite, strontianite, ancylite, biotite, chamosite and ilmenite; thorite, pyrrhotite, sphalerite, galena, monazite, kukharenkoite, synchysite, euxenite and allanite are much less abundant. Minerals such as biotite, chamosite and ilmenite are particularly abundant in thicker veinlets associated with pervasive alteration and oxidation.

#### Fenite

Metasomatic mineral assemblages that can be confidently interpreted as fenite were observed along fractures and in xenoliths hosted by carbonatites and syenites. All known examples of fenitization in the MCV samples are sodic. These metasomatic rocks are composed predominantly of albite and aegirine (Figure 8a), with magnesioarfvedsonite (Na amphibole) observed only in the endocontact zone of calcite carbonatite. At the contact between syenite and fenitized jacupirangite, primary K-feldspar is rimmed by hyalophane and Ba-rich phlogopite (Figure 8b), indicating Ba mobility. In addition to Na- and Ba-silicate phases, fenitization produced several oxide minerals (Figure 8c). Oikocrysts of thorutite (ThTi<sub>2</sub>O<sub>6</sub>) are intergrown with Nbbearing anatase (tetragonal TiO<sub>2</sub>), whereas pyrochlore (Na-Ca-Nb oxide) occurs as inclusions in Nb-bearing brookite (orthorhombic TiO<sub>2</sub>). Titanite crystals in the precursor rock were replaced by ilmenite and calcite. Minor quantities of very fine-grained calcite, ancylite and barytocalcite also occur in the fenitized rocks.

#### **Conclusions and Future Work**

Dolomite, calcite and barytocalcite carbonatites have been identified throughout the Moose Creek valley (MCV). The most abundant carbonatite type, calcite carbonatite, is composed of calcite and minor proportions of dolomite and ferromagnesian silicate minerals. Predominantly dolomitic or barytocalcitic rocks are less common throughout the MCV; however, minor quantities of dolomite and barytocalcite are observed in calcite carbonatites. In MCV dolomite carbonatites, monazite and burbankite are primary, early-crystallizing rare-earth-element (REE)-bearing minerals. Both minerals show evidence of a reaction with postmagmatic fluids, which produced a texturally complex secondary mineral assemblage of Sr-Ba carbonates, barite and apatite. In this assemblage, the principal REE host is ancylite. Monazite is an early-crystallizing REE phase in both dolomite and calcite carbonatites, as indicated by its euhedral equant morphology, occurrence as inclusions in other minerals, and the presence of late-stage reaction assemblages developed at the expense of monazite. All examined calcite carbonatites contain ancylite and apatite; these minerals are most abundant in samples where the replace-



**Figure 8.** Images of fenite assemblages, Ice River Complex, southeastern British Columbia: **a)** plane-polarized light image of aegirine (Aeg)- and albite-rich fenite overprinting syenite; **b)** back-scattered-electron image of the contact between syenite (at left) and fenitized jacupirangite; note a reaction rim of hyalophane (Hya) and phlogopite (PhI) between the two rocks; **c)** BSE image of thorutite (Thrt) oikocrysts intergrown with anatase (Ant) and rimmed by brookite (Brk) containing pyrochlore (PcI) inclusions; the identity of anatase and brookite was confirmed by Raman microspectroscopy. Abbreviations: Ab, albite; Anc, ancylite; Ap, apatite; Cal, calcite; ChI, chlorite; IIm, ilmenite; Kfs, K-feldspar; Ntr, natrolite; Ttn, titanite.



ment of monazite or burbankite is observed. The nature or source of a fluid responsible for this hydrothermal overprint is at present unknown. It can be hypothesized that it was carbonatitic, given the absence of other voluminous intrusives enriched in Sr, Ba and REE in the study area. However, the relative contribution of nonmagmatic sources to this fluid remains to be determined. A study of C-O stable isotope variations in the MCV rocks is presently underway to address this question.

Silica-rich varieties of calcite carbonatite are widespread throughout the MCV; it is not clear if these rocks represent products of silica contamination or crystallized from a silica-rich melt. These rocks are pervasively altered, which resulted in biotite replacement by chlorite and deposition of diverse secondary REE-bearing minerals (monazite, kukharenkoite, synchysite, euxenite and allanite) in association with chlorite. The late-stage REE-bearing minerals are less abundant than monazite and ancylite. An investigation of compositional variability of these minerals, with emphasis on petrogenetically sensitive trace elements (Mn, REEs, Th and U) is currently underway to analyze the distribution of REE among different constituent minerals in the carbonatites and constrain the processes of their formation.

This study recognized barytocalcite carbonatite as a new rock type for the Ice River Complex (IRC). Barytocalcite is accompanied by strontianite and ancylite (as a major REE carrier), which is mineralogically akin to fracture-hosted hydrothermal assemblages observed throughout the MCV. It is therefore possible that this type of carbonatitic magmatism had a larger footprint prior to the exhumation and erosion of the IRC during the Laramide orogeny. The provenance of barytocalcite is presently being investigated using C-O stable isotope, Sr radiogenic isotope and traceelement geochemical analyses.

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