Mineral chemistry and isotopic systematics of carbonatites and related rocks from the Blue River area

Rukhlov, A.S.[1,a], Mao, M.[1], Spence, J.[2], Creaser, R.A.[3], Czech, E.[4], and Gabites, J.[4]
[1] British Columbia Geological Survey, Ministry of Energy, Mines, and Petroleum Resources, Victoria, BC, V8W 9N3;
[2] School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, V8P 5C2
[3] Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, T6G 2E3
[4] PCIGR, Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, V6T 1Z4
[a] corresponding author: Alexei.Rukhlov@gov.bc.ca

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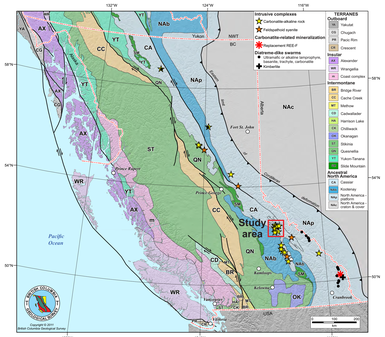
Abstract

Widespread, Late Paleozoic carbonatites in the Canadian Cordillera are unusual. In contrast to most carbonatites, which are restricted to intracratonic settings, they formed in an active tectonic setting, along the western margin of Laurentia. To investigate the sources and evolution of parental magmas at nine 360-330 Ma complexes in east-central British Columbia (Blue River area), we studied isotopic (C-O-S-Sr-Pb-Nd) and elemental compositions of minerals from carbonatites and related rocks. These data reflect relatively hot (757-922 ºC), oxidized (ΔQFM = -0.5 to +5) magmas from heterogeneous, depleted mantle. Isotopic compositions rule out crustal (lithospheric) contamination. A line in the $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ diagram, defined by the compositions of apatites, carbonates, and molybdenite, yields an emplacement age of 324 Ma and reflects various proportions of radiogenic Pb sequestered from coexisting U-rich pyrochlore during metamorphism, constrained by the molybdenite Re/Os model age of 175 Ma. In the Sr-Pb-Nd isotopic diagrams using the lowest initial $^{206}Pb/^{204}Pb$, the Blue River rocks follow the mixing trend involving FOZO and EM1 mantle end-members found in oceanic island basalts, young (<200 Ma) carbonatites worldwide, and the plume-related Kola alkaline province (380 Ma). Thus, the Blue River carbonatites are mineralogically and isotopically indistinguishable from worldwide carbonatites generated by deep-mantle plumes. Was the back-arc extension from eastward subduction that led to the Slide Mountain ocean triggered by a mantle plume?



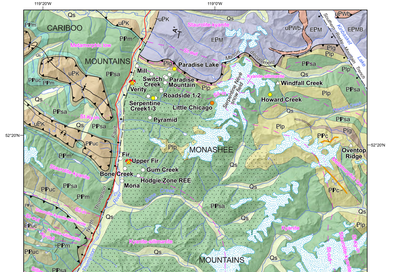
Location of study area and distribution of carbonatite-alkaline complexes (Neoproterozoic, Cambrian and Late Devonian-Mississippian) and dike-diatreme swarms (Ordovician, Late Devonian and Middle Triassic; Pell, 1994; Millonig et al., 2012). Geology from Colpron and Nelson (2011).

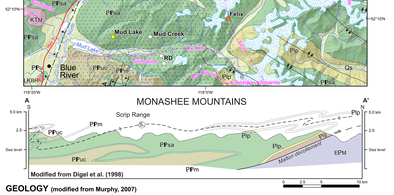
Introduction

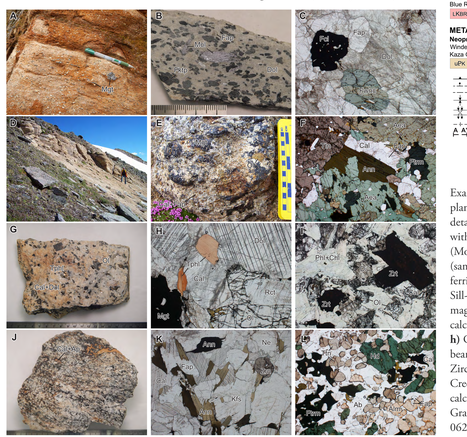
We examined petrography, mineral chemistry, and isotopic systematics (C-O-S-Sr-Pb-Nd plus Re/Os on molybdenite) of carbonatites and related rocks from nine intrusive complexes in the Blue River area, east-central British Columbia to investigate their origin and Nb-Ta-REE mineralization. Separated mineral fractions (carbonates, silicates, oxides, sulphides, apatite) from 34 rock samples were analyzed by EPMA and LA-ICP-MS (plus in situ analysis), solution MC-ICP-MS, TIMS, and IRMS using standard methods (details are available from authors).

Geological setting

The study area lies within the Omineca belt and is characterized by penetrative, amphibolite-facies foliation and syntectonic plutonism. Several carbonatite-ultramafic and alkaline-rock intrusive complexes (ca. 500 and 360-330 Ma) and the enclosing (semi)pelites and amphibolites of the Mica Creek assemblage (750-550 Ma) mark rifting and breakup of Rodinia, followed by the development of the western Laurentia margin. These rocks underwent multiphase deformation, anatexis, and exhumation during the subsequent Cordilleran orogeny (Pell, 1994; Digel et al., 1998; Millonig and Groat, 2013). The area hosts two carbonatite-hosted Nb-Ta deposits. Upper Fir is the largest and best-studied deposit, containing 48.4 million tonnes (indicated category) at 1,610 ppm Nb_2O_5 and 197 ppm Ta_2O_5 plus 5.4 million tonnes (inferred category) at 1,760 ppm Nb_2O_5 and 191 ppm Ta_2O_5 (Kulla and Hardy, 2015). Ore minerals are mainly Ta-rich pyrochlore and ferrocolumbite, with minor fersmite among others (Chudy, 2013).







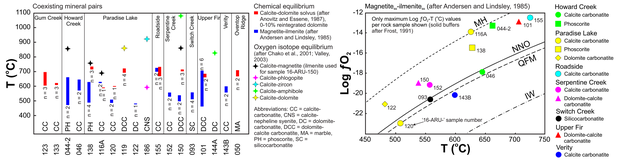
Examples of carbonatites and related rocks of the Blue River area (**c, f, h, i, k, l** plane-polarized light photomicrographs, field of view 5 mm; see table for sample details and abbreviations). **a)** Weathered surface of foliated dolomite-carbonatite with apatite (white) and magnetite (Mgt) porphyroclasts, Upper Fir. **b)** Molybdenite (Mol) in foliated, ferrikatophorite (Fktp)-rich dolomite-carbonatite, Upper Fir (sample 16-ARU-198). **c)** Granoblastic texture in ferrocolumbite (Fcl)- and ferriwinchite (Fwnc)-bearing dolomite-carbonatite, Upper Fir (16-ARU-072). **d)** Sill-like body of calcite-carbonatite, Howard Creek. **e)** Cumulate texture in magnetite-rich phoscorite, Howard Creek. **f)** Poikilo-porphyroblastic texture in calcite-titanite-amphibole clinopyroxenite, Howard Creek (16-ARU-042-2). **g) and h)** Granoblastic texture in foliated, olivine (Ol)- and tetraferriphlogopite (Tphl)-bearing, dolomite-calcite carbonatite, Serpentine Creek (16-ARU-150). **i)** Zirconolite (Zrt) in foliated, phlogopite (Phl)- and olivine-rich carbonatite, Switch Creek (16-ARU-093). **j) and k)** Lepidoblastic-porphyroclastic texture in foliated, calcite (Cal)-bearing nepheline-syenite, Paradise Lake (16-ARU-116A). **l)** Granoblastic texture in titanite (Ttn)-rich, exocontact fenite, Upper Fir (16-ARU-062-1).

Petrography and mineral chemistry

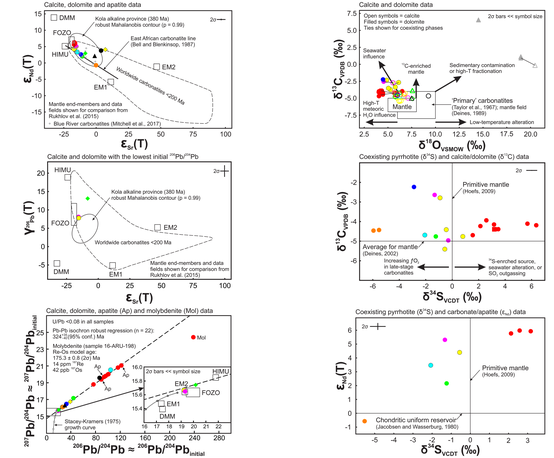
Sample[1]	Rock type	Texture	Mineralogy: Major	Mineralogy: Minor and accessory	Notes
Gum Creek (119°07'48.45" W, 52°17'48.20" N)					
16-ARU-123	Calcite carbonatite	Foliated, porphyroclastic, medium-grained matrix	Cal, Fap-Hap, Fktp-Marf	Phl, Pcl, Zrn, Ilm, Ep, Po, Ccp	Dol ex in Cal; brown-red U-Ti-rich Pcl; Fe^{2+}-Na-Ti-rich Phl; Nb-bearing, Fe^{3+}-rich Ilm
16-ARU-133	Calcite carbonatite	Foliated, porphyroclastic, medium-grained matrix	Cal, Fap-Hap, Fktp	Phl-Tphl, Fcl, Pcl, Ilm, Ep, Po	Dol ex in Cal; dark red Pcl; Fe^{2+}-Ti±Na-rich Phl-Tphl; Mg-Ti-rich Fcl; Nb-bearing, Fe^{3+}-rich Ilm
Howard Creek (118°53'17.67" W, 52°23'17.00" N)					
16-ARU-046	Calcite carbonatite	Foliated, coarse-grained, granoblastic	Cal, Fap-Hap, Ol, Mgt	Ilm, Phl, Ed, Zrn, Bdy, Zrt, Po	Fo_{6C} Na-rich Phl; low-X (Fe-rich) Pc; Hf-rich Zrn (1 cm crystals) in talus
16-ARU-040	Calcite-nepheline syenite	Coarse-grained, poikilo-granoblastic	Ab, Ne, Ftrm, Cal	Fap, Aea, Ttn, Scp, Ccn, Amn, Po	Fe-Nb-Zr-rich Ttn; St-rich Fap; Al-Fe^{2+}-Mg-rich Aea
16-ARU-042-2	Calcite-titanite-amphibole clinopyroxenite	Coarse-grained, nemato-poikilo-porphyroblastic	Aea, Ftrm, Ttn, Ann, Cal	Fap, Ab	Al-Fe^{2+}-Mg-rich Aea; Mg-Ti-rich Ann
16-ARU-044-2	Phoscorite	Coarse-grained, cumulate	Ol, Mgt, Ilm, Cal	Fap-Hap, Ath, Zrn, Bdy, Chn	Fo_{33-41}; Zn-bearing, Mg-rich Ilm; V-bearing Mgt
Mill (119°08'51.22" W, 52°25'10.61" N)					
16-ARU-171	Calcite clinopyroxenite	Coarse-grained, cumulate-nematoblastic	Aea-Omp, Cal, Fap-Hap	Phl	Na-Al-Fe^{2+}-Ti-rich Phl; Fe^{3+}-Mg-rich Omp to Al-Mg-rich Aea
Paradise Lake (119°05'03.28" W, 52°24'37.95" N)					
16-ARU-116A	Calcite-carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Cal, Fap, Mgt, Phl	Ol, Ed, Zrn, Po, Gth	$Fo_{5?}$; Na-rich Phl; Zn-bearing, Fe-rich Gk ex in V>Mg-bearing Mgt
16-ARU-120	Calcite-carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Cal, Fap, Tphl, Mgt	Ol, Chn, Ed?, Po, Gth	Sub-µm Dol ex in Cal; Zn-bearing, Mg-rich Ilm ex in V>Zn-bearing Mgt
16-ARU-119	Dolomite-calcite carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Cal>Dol, Ol, Rct, Ilm	Tphl, Fap, Zrn, Po, Ccp, Cbn, Srp	Fo_{79-80}; Dol ex in Cal; Hf-rich Zrn; low-X (Fe-rich) Po; Nb±Cr-bearing, Mg_2Fe^{3+}-rich Ilm
16-ARU-122	Dolomite carbonatite	Coarse-grained, granoblastic	Dol, Fap	Kct, Mgt, Ilm, Tphl, Fcl, Gth, Chl	Fe-rich Dol; V-bearing Mgt; Nb-bearing, Fe^{2+}-rich Ilm
16-ARU-132	Dolomite carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Dol, Fap, Ts-Kct	Mgt, Po, Py, Phl, Fcl?, Chl	Fe-rich Dol; V-bearing Mgt; Co-rich Py
16-ARU-177	Silicocarbonatite	Foliated, coarse-grained, sideronitic-cumulate	Dol>Cal, Ol, Rct, Mgt, Chn	Zrn, Phl, Srp	Fo_{80-81}; Ti-bearing Mgt; Ti-Fe-rich Chn; Hf-rich Zrn
16-ARU-183	Silicocarbonatite	Foliated, coarse-grained, poikilo-nematoblastic	Mbs, Di-Aug, Cal, Fap	Phl, Chl	Fe^{3+}-Na±Fe^{2+}-rich Di to Aug; Fe^{2+}-Ti-Na-rich Phl
16-ARU-138	Phoscorite	Coarse-grained, sideronitic-cumulate-porphyroclastic	Ol, Mgt, Cal, Fap-Hap, Rct	Pcl, Tphl, Py, Po, Zrn, Zrt, Srp	Fo_{44-45}; Dol ex in Cal; orange-brown U-Ta-Ti-rich Pcl; Ta-Nb-rich Zrt; Na-rich Tphl; Mn-Fe^{2+}-Fe^{3+}-rich Gk to Mn-Mg±Fe^{2+}-rich Ilm ex in V>Mg-bearing Mgt
16-ARU-126	Fenite	Foliated, medium-grained, nemato-granoblastic	Rct-Fktp, Aea, Cal, Fap	Ab, Kfs, Zrn	Al-Mg±Fe^{2+}-rich Aea
16-ARU-186	Calcite-nepheline syenite	Foliated, medium-grained, lepidoblastic-porphyroclastic	Ab, Kfs, Ne, Sdl, Ann, Cal, Fap	Zrn, Ccn, Pcl, opq	Mg-Al-Ti-rich Ann; Hf-rich Zrn; red-brown Pcl
Roadside (119°06'57.74" W, 52°23'32.96" N)					
16-ARU-155	Calcite carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Cal, Fap, Ol	Zrn, Tphl, Rct, Py, Po, Mgt, Pcl	Dol ex in Cal; orange Pcl; ubiquitous Zrn; Na-rich Tphl; Zn-bearing, Mg-Fe^{3+}-rich Ilm ex in V>Mg±Mn-bearing Mgt
Serpentine Creek (119°00'52.71" W, 52°22'55.31" N)					
16-ARU-152	Calcite-carbonatite	Foliated, porphyroclastic, fine-grained matrix	Cal, Fap, Ol, Di, Phl, Mgt	Ed, Ilm, Po, Zrn, Srp	Fo_{55-66}; ubiquitous fine-grained Zrn aggregates; Na-rich Phl; Zn-bearing, Mg-rich Ilm ex in V≤Zn≤Al-bearing Mgt; Nb-bearing, Mg-Fe^{3+}-rich Ilm
16-ARU-150	Dolomite-calcite carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Cal>Dol, Ol, Tphl, Rct-Kct, Mgt, Ilm	Fap, Po, Ccp	Fo_{71-76}; coarse to sub-µm Dol ex in Cal; rare PbS-SrO$_2$ globules (~1 mm); Mg-rich Ilm ex in Cr-V-bearing Mgt; Nb-bearing, Mg-Fe^{3+}-rich Ilm
Switch Creek (119°07'15.28" W, 52°24'40.72" N)					
16-ARU-093 (S07-002/44.70-57.90)	Silicocarbonatite	Foliated, medium-grained, cumulate-porphyroclastic, fine-grained matrix	Ol, Phl, Di, Cal, Zrt, Chl, Srp	Fap, Mgt, Ilm	Fo_{4C} Na-rich Phl; Mg-rich Ilm (Mn-rich inclusions in Zrt); V≤Mg±Mn-bearing, ±Ti-rich Mgt; Nb-rich Zrt
Upper Fir (119°09'28.13" W, 52°18'17.40" N)					
16-ARU-006	Dolomite carbonatite	Foliated, porphyroclastic, fine-grained matrix	Dol, Fap, Fktp	Cal, Po, Mgt, Pcl	Orange-red, U-Ta-rich Pcl; Fe-rich dolomite
16-ARU-072 (F06-001/74.64-74.76)	Dolomite carbonatite	Foliated, coarse-grained, granoblastic	Dol, Fap, Fwnc-Act	Po, Mgt, Phl, Zrn, Fcl, Pcl	Brown-red to dark-orange Pcl; ubiquitous Zrn; Fe-rich Dol; Fe^{2+}-rich Phl; V-bearing Mgt; Mg>Ta-rich Fcl
16-ARU-089 (F06-001/67.78-67.90)	Dolomite carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Dol, Fap, Mlhb-Act	Po, Fcl, Pcl	Fe-rich Dol; ubiquitous Ni-rich Po; orange, Na-deficient, Fe-Ta-rich Pcl; Mg≥Ta-rich Fcl
16-ARU-104 (F06-001/66.67-66.79)	Dolomite carbonatite	Foliated, coarse-grained, nemato-granoblastic	Dol, Fap, Rct, Po	Cal, Pcl	Act-Po segregation; Fe-rich Dol; Ni-rich Po
16-ARU-111 (F06-001/99.71-99.74)	Dolomite carbonatite	Foliated, coarse-grained, granoblastic	Dol, Fap, Act	Po, Fcl, Frs, Cal, Ccp, Pcl	Fe-rich Dol; Fap segregation with abundant Fcl>Pcl (orange, rare)-Frs aggregates (1 cm); Mg≥Ta-rich Fcl
16-ARU-144	Dolomite carbonatite	Foliated, porphyroclastic, fine-grained matrix	Dol, Fap, Fktp	Po, Mgt, Pcl, Zrn	Fe-rich Dol; orange, Ta≥Fe-U-rich Pcl (±Frs?); Py mantle on Fap inclusion in Pcl
16-ARU-198 (F07-023/123.84-123.90)	Dolomite carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Dol, Fap, Fktp	Mol, Po, Ccp, Pcl	Fktp segregation with ~2% Mol books (up to 17 mm wide); Fe-rich Dol; orange-red, Ti-U-Ta-rich Pcl
16-ARU-101 (F06-001/76.85-77.00)	Calcite-dolomite carbonatite	Coarse-grained, sideronitic-granoblastic	Dol>Cal, Fap, Fktp-Rct, Mgt	Pcl, Ilm, Zrn, Fcl, Po, Phl, Ccp	Coarse to sub-µm Dol ex in Cal; Fe-rich Dol; ubiquitous orange, U-Ta-rich Pcl; rare Na-Ca-deficient, U-Fe-Ta-rich Pcl; Fe^{2+}-Na-rich Phl; Fe^{2+}-rich Ilm; Ilm ex in Ti-bearing Mgt; Mg-Ta-rich Fcl
16-ARU-082 (F06-005/127.12-127.41)	Dolomite-calcite carbonatite	Coarse-grained, granoblastic-porphyroclastic	Cal>Dol, Fap, Fktp, Mgt	Po, Pcl, Zrn	Massive Po-Fap-Mgt aggregates (up to 4 cm wide); lamellar Dol ex in Cal; Fe-rich Dol; orange, U-Ta-rich Pcl; Ti-bearing Mgt
16-ARU-062-1 (F06-017/105.41-105.47)	Fenite	Medium-grained, granoblastic	Hd, Alm, Ttn, Ab	Cal, Ftrm?, Kfs, Fap?, Po	Mg-Fe^{2+}-rich Hd
Verity (119°09'20.03" W, 52°23'57.10" N)					
16-ARU-143B	Calcite carbonatite	Foliated, coarse-grained, granoblastic-porphyroclastic	Cal, Hap-Fap, Ol, Phl, Di	Mgt, Po?, Srp, Ilm, Zrt	Fo_{5C} Na-rich Phl; Nb-rich Zrt; Nb-bearing, Mg-rich Ilm; Mg-Mn-V-Al-bearing, Ti-rich Mgt
16-ARU-175	Dolomite carbonatite	Foliated, porphyroclastic, fine-grained matrix	Dol, Fap, Tphl	Kfct, Mgt, Po, Pcl, Fcl	Fe-rich Dol; Fe^{2+}-rich Tphl; brown-red, Ft≥Ta-rich Pcl; orange, F-Sr-rich Pcl; Mg-rich Fcl (inclusions in brown-red Pcl)
Ovontop Ridge (118°43'47.41" W, 52°19'55.43" N)					
16-ARU-050	Dolomite-calcite marble	Foliated, coarse-grained, nematoblastic-porphyroclastic	Cal>Dol, Tr	Phl, Gr?	Dol ex in Cal
Windfall Creek (118°52'24.93" W, 52°24'12.94" N)					
16-ARU-048	Calcite marble	Foliated, medium-grained, granoblastic	Cal	Gr, Qz, Ab, Kfs, Ms, Py	

Abbreviations: **Aea** = aegirine-augite, **Ab** = albite, **Act** = actinolite, **Alm** = almandine, **Ann** = annite, **Ath** = anthophyllite, **Aug** = augite, **Bdy** = baddeleyite, **Cal** = calcite, **Cbn** = cubanite, **Ccn** = cancrinite, **Ccp** = chalcopyrite, **Chl** = chlorite, **Chn** = chondrodite, **Di** = diopside, **Dol** = dolomite, **Ed** = edenite, **Ep** = epidote, **ex** = exsolution, **Fap** = fluorapatite, **Fcl** = ferrocolumbite, **Fktp** = ferrikatophorite, **Fo** = forsterite end-member (mol%) in olivine, **Frs** = fersmite, **Ftrm** = (ferro)ferritaramite, **Fwnc** = ferriwinchite, **Gk** = geikielite, **Gr** = graphite, **Gth** = goethite, **Hap** = hydroxylapatite, **Hd** = hedenbergite, **Ilm** = ilmenite, **Kfs** = K-feldspar, **Kfrct** = K-fluorrichterite, **Kct** = K-richterite, **Marf** = magnesio-arfvedsonite, **Mhb** = magnesiohorblendite, **Mgt** = magnetite, **Mbs** = magnesiohastingsite, **Mol** = molybdenite, **Ms** = muscovite, **Ne** = nepheline, **Ol** = olivine, **Omp** = omphacite, **opq** = opaque, **Pcl** = pyrochlore, **Phl** = phlogopite, **Po** = pyrrhotite, **Py** = pyrite, **Qz** = quartz, **Rct** = richterite, **Sdl** = sodalite, **Scp** = scapolite, **Srp** = serpentine, **Tr** = tremolite, **Tphl** = tetraferriphlogopite, **Ttn** = titanite, **Zrn** = zircon, **Zrt** = zirconolite. [1] Drill hole number and depth (m) from surface in parentheses.

Thermobarometry



Isotopic systematics



Summary

The Blue River carbonatites formed from relatively hot (757-922 ºC), oxidized (ΔQFM = -0.5 to +5) parental magmas, derived from a heterogeneous, sublithospheric mantle, involving mixing of FOZO and EM1 end-members, which are found in oceanic island basalts, young (<200 Ma) carbonatites worldwide, and plume-related Kola alkaline province (380 Ma). Thus, the Blue River carbonatites are indistinguishable from worldwide carbonatites generated by plumes of deep-mantle origin.

Acknowledgements
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