Preliminary Insights into Carbonatite Genesis, and Future Directions Using Uranium-Lead Zircon Ages and Hafnium Isotopic Signatures of Alkaline Rocks from the Canadian Cordillera, Southeastern British Columbia (Parts of NTS 082L, M, 083D)

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Introduction

Carbonatites are uncommon igneous rocks (Bell et al., 1999) that contain over 30% primary carbonate minerals (Mitchell, 2005) and are of considerable economic interest due to their enrichment in rare-earth elements (REEs) and niobium, making carbonatites the major source of these elements in the world (Rankin, 2005). In addition to their economic importance, carbonatites are critical for understanding mantle processes and tectonic history. Their frequent occurrence in Precambrian cratonic areas (~88%) and association with extensional tectonics or continental rifting (Bell and Tilton, 2001; Veevers, 2007) make them valuable markers for reconstructing past continental configurations. Their distinctive geochemical signatures, characterized by a high hafnium content, enable radiogenic isotope studies that can provide insights into the composition and evolution of the subcontinental mantle.

Despite significant advances in understanding carbonatites, several key questions remain unresolved, particularly concerning their mantle source regions and genesis. Geochemical studies have linked carbonatite formation to the chemical heterogeneity of the mantle, with different isotopic compositions, such as depleted mid-ocean–ridge basalt (MORB) mantle (DMM), high-µ (HIMU) and enriched mantle (EM) types, associated with carbonatites and oceanic-island basalts (OIBs). Whereas OIBs provide insights into the sub-oceanic mantle, carbonatites, predominantly found in continental settings, offer a window into the subcontinental mantle. However, there is ongoing debate regarding whether carbonatites originate from distinct mantle components or from heterogeneous lithospheric mantle sources. For example, carbonatites from the East African Rift have been attributed to mantle-plume metasomatism (Bell and Tilton, 2001), whereas alternative interpretations suggest a localized lithospheric source without plume involvement (Woolley and Bailey, 2012). The lack of consensus on these issues highlights the need for further isotopic and geochemical research to clarify the processes driving carbonatite genesis and mantle heterogeneity. The formation of carbonatites and their potential to become ore-grade deposits are controlled by factors such as the source region of the parent magma, the depth and degree of melting, and the subsequent evolution of the magma during its ascent and emplacement (Simandl and Paradis, 2018).

Preliminary results and discussion aimed at addressing the gaps in understanding the processes leading to carbonatite formation are presented in this paper, focusing specifically on an area of the Canadian Cordillera in southeastern British Columbia (BC). Late Devonian–Early Mississippian alkaline magmatism in this region offers a unique opportunity to investigate mantle processes at a point of significant tectonic transition from passive to active along the western Laurentian margin. The primary objective of future research will be to investigate the timing and mantle source characteristics of carbonatite and syenite magmatism, with a focus on testing the hypothesis that this activity reflects the involvement of a metasomatized mantle source. By integrating new zircon U-Th-Pb geochronological data with Hf isotopic signatures, future research will aim to clarify the role of tectonic processes and mantle heterogeneity in

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driving alkaline magmatism during this period of tectonic transition to a subduction zone setting. An introduction to these ongoing investigations is presented in this preliminary paper that serves as a foundation for forthcoming studies, which will contribute to a broader understanding of the role of metasomatized mantle sources in shaping carbonatite genesis.

Regional Geology

The Canadian Cordillera can be subdivided into five morphogeological belts from west to east: the Insular, Coast, Intermontane, Omineca and Foreland belts (Figure 1a; Monger et al., 1982; Monger and Price, 2002). The Omineca belt represents the westernmost section of the miogeocline of the North American craton, where allochthonous terranes are structurally juxtaposed with parautochthonous (Kootenay terrane) and autochthonous North American margin. The study area is located within the southern Omineca belt (Figure 1a, b) and comprises two tectonic terranes: the Selkirk allochthon and the Monashee Complex. The Selkirk allochthon features deformed and metamorphosed rocks from accreted terranes, metasedimentary strata and mafic sills thrust over the Monashee Complex, which includes basement rocks and a cover sequence of metasedimentary and metavolcanic units (Read and Brown, 1981).

Carbonatites and associated alkaline rocks in the Canadian Cordillera are restricted to the Omineca and Foreland belts (Figure 1a), where they intruded or erupted in contact with Neoproterozoic and early to middle Paleozoic miogeoclinal strata during periods of rifting or extensional tectonics (Okulitch, 1984; Parrish and Scammell, 1988; Pell, 1994). There have been three distinct episodes of alkaline magmatism within the Cordillera, spanning approximately 460 m.y. (Millonig et al., 2012). The youngest and most extensive episode occurred around 360–340 Ma (Figure 1b), associated with extensional tectonics related to a back-arc regime during the early stages of subduction along the western margin of Laurentia (Pell, 1994; Nelson and Colpron, 2007).

Local Geology

Blue River Area (BRA)

The Blue River area (BRA) is underlain by the Selkirk allochthon, situated structurally above the Paleoproterozoic basement represented by the Malton and Monashee complexes (Figure 1b; Digel et al., 1998). It is bounded by the North Thompson normal fault to the west and the Rocky Mountain Trench to the east (Figure 1b; Struik, 1993). The area features brittle normal faults and folds, collectively known as the Selkirk fan, characterized by a southwestward to northeastward change in vergence (Ewing, 1981; Gibson et al., 2008). The Trident Mountain syenite occurs on the eastern flank of the fan, where the deepest crustal levels are exposed (Figure 1b).

The principal lithological unit in the BRA is the Neoproterozoic Horsethief Creek Group, a clastic turbidite sequence that forms the basal succession of the upper Proterozoic and Paleozoic Cordilleran miogeocline (Figure 1b; Wheeler, 1965; Brown, 1978; Perkins, 1983). It is overlain by the upper Paleozoic–lower Cambrian Hamill Group quartzites, the lower Cambrian Badshot Formation marbles and the deep-water facies of the lower Paleozoic Lardeau Group, which includes carbonates and metavolcanics (Figure 1b; Colpron et al., 2002). Approximately 18 carbonatites and accompanying alkaline rocks in the BRA occur as sill-like bodies and lenses that intruded these units during the late Cambrian and Late Devonian–Late Mississippian (Figure 1b; Millonig et al., 2012). The Trident Mountain syenite (TMS) is found within a lower pelite unit in the eastern part of the BRA.

Frenchman Cap Dome (FCD)

The Monashee Complex, which includes the Frenchman Cap dome (FCD), represents the deepest exposed structural level within the Shuswap metamorphic core complex (Figure 1b; Monger et al., 1982; Okulitch, 1984). The FCD is bounded to the west by the Monashee décollement, a ductile reverse shear zone, and to the east by the Columbia River fault (Figure 1b). The Mount Grace carbonatites are located on an overturned limb of the Mount Grace syncline, a west-verging fold nappe. The Three Valley gap (TVG) alkaline rocks occur in the southwestern part of the FCD, within a series of tightly spaced normal faults related to the Victor Lake fault.

The Monashee core gneiss comprises Proterozoic orthogneiss and subordinate paragneiss and is unconformably overlain by the Monashee cover gneiss, which includes a Mesoproterozoic to Late Devonian metasedimentary sequence (Figure 1b; Wheeler, 1965; Reesor and Moore, 1971). Within the FCD, carbonatites and alkaline rocks ap-

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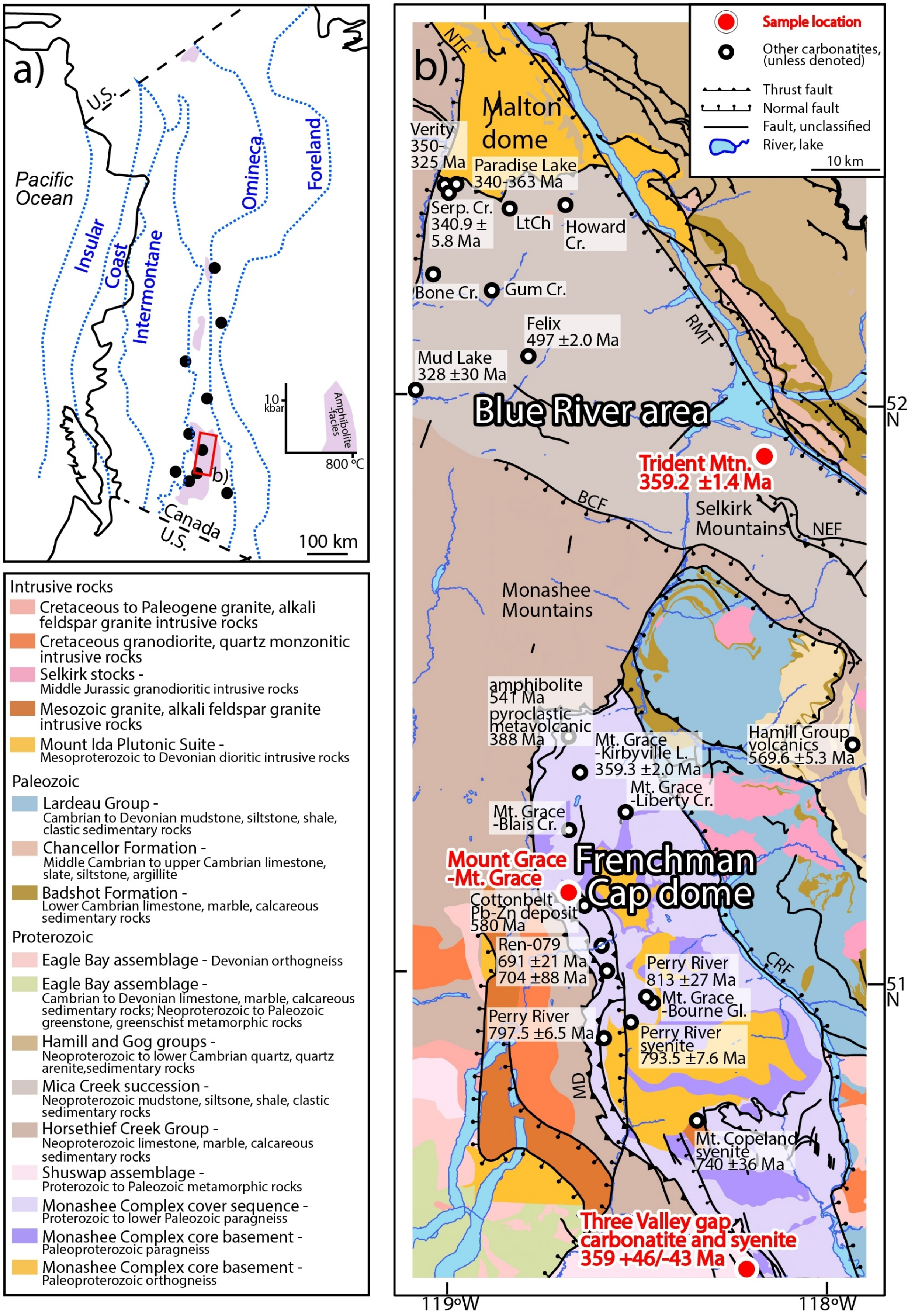
Figure 1. Morphogeological belts of the Canadian Cordillera and generalized geology of the study area: **a)** distribution of carbonatite and alkaline complexes (black dots) in western North America (after Pell, 1994; McMillan and McLemore, 2004; Lund, 2008; Woolley and Kjarsgaard, 2008; Millonig et al., 2012) and simplified map showing the boundaries (blue dashed lines) of the five morphogeological belts (modified from Monger and Price, 2002), the pressure-temperature diagram of amphibolite-facies metamorphism (purple polygon) and the study area (red box); **b)** sample localities (red dots) plotted on a tectonic assemblage map of the study area, and other carbonatite and syenite localities plotted (small white dots) with igneous ages (after Parrish and Scammell, 1988; Pell, 1994; Parrish, 1995; Colpron et al., 2002; Millonig et al., 2012). Abbreviations: BCF, Birch Creek fault; Cr., creek; CRF, Columbia River fault; Gl., glacier; L., lake; LtCh, Little Chicago; MD, Monashee décollement; Mt., mount; Mtn., mountain; NEF, Northeast fault; NTF, North Thompson fault; RMT, Rocky Mountain Trench; Serp., Serpentine.


a)
U.S.
Pacific Ocean
Insular
Coast
Intermontane
Omineca
Foreland
10 kbar
Amphibolite -facies
800 °C
b)
Canada
U.S.
100 km
Intrusive rocks
Cretaceous to Paleogene granite, alkali feldspar granite intrusive rocks
Cretaceous granodiorite, quartz monzonitic intrusive rocks
Selkirk stocks - Middle Jurassic granodioritic intrusive rocks
Mesozoic granite, alkali feldspar granite intrusive rocks
Mount Ida Plutonic Suite - Mesoproterozoic to Devonian dioritic intrusive rocks
Paleozoic
Lardeau Group - Cambrian to Devonian mudstone, siltstone, shale, clastic sedimentary rocks
Chancellor Formation - Middle Cambrian to upper Cambrian limestone, slate, siltstone, argillite
Badshot Formation - Lower Cambrian limestone, marble, calcareous sedimentary rocks
Proterozoic
Eagle Bay assemblage - Devonian orthogneiss
Eagle Bay assemblage - Cambrian to Devonian limestone, marble, calcareous sedimentary rocks; Neoproterozoic to Paleozoic greenstone, greenschist metamorphic rocks
Hamill and Gog groups - Neoproterozoic to lower Cambrian quartz, quartz arenite,sedimentary rocks
Mica Creek succession - Neoproterozoic mudstone, siltstone, shale, clastic sedimentary rocks
Horsethief Creek Group - Neoproterozoic limestone, marble, calcareous sedimentary rocks
Shuswap assemblage - Proterozoic to Paleozoic metamorphic rocks
Monashee Complex cover sequence - Proterozoic to lower Paleozoic paragneiss
Monashee Complex core basement - Paleoproterozoic paragneiss
Monashee Complex core basement - Paleoproterozoic orthogneiss
b)
Sample location
Other carbonatites, (unless denoted)
Thrust fault
Normal fault
Fault, unclassified
River, lake
10 km
NTF
Malton dome
Verity 350-325 Ma
Paradise Lake 340-363 Ma
Serp. Cr. 340.9 ± 5.8 Ma
LtCh
Howard Cr.
Bone Cr.
Gum Cr.
Felix 497 ±2.0 Ma
Mud Lake 328 ±30 Ma
RMT
Blue River area
52° N
Trident Mtn. 359.2 ±1.4 Ma
BCF
Selkirk Mountains
NEF
Monashee Mountains
amphibolite 541 Ma
pyroclastic metavolcanic 388 Ma
Mt. Grace -Kirbyville L. 359.3 ±2.0 Ma
Hamill Group volcanics 569.6 ±5.3 Ma
Mt. Grace -Liberty Cr.
Mt. Grace -Blais Cr.
Mount Grace -Mt. Grace
Frenchman Cap dome
Cottonbelt Pb-Zn deposit 580 Ma
Ren-079 691 ±21 Ma 704 ±88 Ma
Perry River 813 ±27 Ma
CRF
51° N
Mt. Grace -Bourne Gl.
Perry River 797.5 ±6.5 Ma
Perry River syenite 793.5 ±7.6 Ma
MD
Mt. Copeland syenite 740 ±36 Ma
Three Valley gap carbonatite and syenite 359 +46/-43 Ma
119°W
118°W

pear as large, sill-like bodies that intruded or erupted into the basal few hundred metres of the Monashee cover gneiss (Höy, 1987; Scammell and Brown, 1990). The Mount Grace carbonatites (MGCs) are located within the upper cover gneiss and the TVG rocks are located within the lower cover gneiss of the Monashee Complex.

Zircon Isotopic Sampling Program

Previous Geochronological Studies

This study focuses on the TMS, MGC and TVG carbonatite and syenite, each of which has been the subject of previous geochronological analyses. Table 1 lists the locations of samples from this study and related carbonatites and syenites along with any known igneous or metamorphic age. Millonig et al. (2012) conducted U-Pb zircon analysis on the TMS, this syenite yielding an inferred intrusion age of ca. 360 Ma, along with a metamorphic age of ca. 57 Ma, based on the observed linear discordia arrays. Millonig et al. (2012) also investigated zircon from the MGC at the Blais Creek location, concluding that the eruption age was ca. 359.3 ±2 Ma. Parrish (1995) analyzed samples from the MGC at Blais Creek and determined that the growth of metamorphic zircon occurred at ca. 55 Ma, indicating significant post-eruption metamorphism. Uranium-lead analysis of zircon from an intrusive carbonatite gneiss near the Three Valley gap locality by Parrish (1995) suggested an intrusion age of 359 ±46 Ma for the TVG carbonatite and syenite. Notably, the TVG syenite has not been previously dated, making this study crucial for establishing its geochronological context.

Methods

Zircon grains were separated using conventional density and magnetic methods. The entire separate was annealed in a muffle furnace at 900 °C for 60 hours to repair radiation damage, enhance cathodoluminescence (CL) emission and improve laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) performance. After annealing, individual grains were hand-picked, mounted, polished and imaged via CL using a scanning electron microscope (SEM), and spots for LA-ICP-MS analysis were selected.

Uranium, thorium and lead isotope analyses were performed using LA-ICP-MS at the Goethe-Universität Frankfurt, following the method presented in Gerdes and Zeh (2006, 2009), with slight modifications. A Thermo-Scientific Element II High Resolution ICP-MS was coupled with a 193 nm excimer laser system for ablation. Spot sizes ranged from 17 to 80 µm, depending on uranium content. Data were acquired in time-resolved mode, with a 20 second background measurement followed by 21 seconds of sample ablation. Raw data were corrected offline for background signal, common lead, elemental fractionation and instrumental mass bias using an in-house spreadsheet program. The method was verified using reference zircon samples.

Hafnium isotopes were measured in zircon by monitoring masses ^{172}Yb, ^{173}Yb, ^{175}Lu and ^{176}Hf, with isobaric interference corrections applied. Bias corrections used an exponential law (based on ^{179}Hf/^{177}Hf = 0.7325) and the GJ-1 zircon served as the reference standard. The average ^{176}Hf/^{177}Hf value obtained for GJ-1 was 0.282008 ±16 (2σ), consistent with published values.

Sample Descriptions

Blue River Area

The Trident Mountain syenite is a concordant lenticular body within the lower pelite unit of the Horsethief Creek Group rocks and outcrops of the Selkirk terrane on the slopes of Trident Mountain and adjacent ridges (Perkins, 1983; Pell, 1994). The syenite is white to gray, medium grained and moderately well foliated parallel to the margins of the intrusive body, with compositional layering (Perkins, 1983; Pell, 1994). Sample TMS (Table 1) is a nepheline-syenite gneiss composed of K-feldspar (30–40 vol. %), nepheline (34–45 vol. %), plagioclase (10 vol. %), sodalite (2–5 vol. %) and biotite (~2 vol. %), with accessory zircon and pyrochlore.

Frenchman Cap Dome

The Mount Grace carbonatites are pyroclastic deposits and occur as thin (~0.5–4 m), laterally discontinuous strata-bound mappable lenses on a single stratigraphic horizon within the Monashee cover gneiss (Höy and McMillan, 1979; Höy, 1987). They can be traced and projected for at least 60 km along strike on the inverted southwestern limb of the Mount Grace syncline (Figure 1; Höy, 1987; Pell, 1994). The Mount Grace carbonatites (at Blais Creek, Mount Grace, Perry River and Bourne Glacier; Figure 1b) were extensively described in Abdale et al. (2024) and comprise a range of lithofacies, from tuffs, lapilli tuffs and tuff breccias to country-rock breccia. Sample MGC (Table 1) is a calciocarbonatite from the Mount Grace location; it is a brown- to black-weathered, massive to poorly bedded and mildly foliated clast-supported lapilli tuff that is poorly sorted and weakly normally graded. The grains appear to be ~75–85% juvenile carbonatitic in composition, with ~15–25% albite-rich xenoliths.

The Three Valley gap carbonatite and syenite occur as thin, discontinuous bedding-parallel lenses within the Monashee cover gneiss. Carbonatite lenses are generally 20–60 cm in width and have mafic fenites 10–30 cm thick developed between them and adjacent rocks. Everywhere they were observed, the fenites are in direct contact with, and gradational to, syenites. Commonly the carbonatite occurs as lenses within the fenite. Sample TVG-C (Table 1) is

Table 1. Rock type, sample name, coordinates and geochronological data for the Blue River and Frenchman Cap dome areas.

Area	Name/ rock type	Sample	Latitude (N), longitude (W)	U/Th-Pb age (Ma ±2σ)	Phase (method)	Interpretation	Source	Sample description and other information
Blue River area	Trident Mountain syenite	**TMS**	**51°53'38.48", 118°05'43.25"**					Intrusive; foliated
		TR-042-1	51°53'38.48", 118°05'43.25"	359.2 ±1.4	Zircon (weighted average)	Igneous age	Millonig et al. (2012)	
		TR-042-1		57.2 ±1.2	Zircon (lower intercept)	Metamorphic age	Millonig et al. (2012)	
		Unnamed	51°54"00", 118°09'00"	378 ±7	Zircon (upper intercept)	Igneous age	Pell (1994)	
		Unnamed		138 ±9	Zircon (lower intercept)	Metamorphic age	Pell (1994)	
		Unnamed		60	Pyrochlore (weighted average)	Metamorphic age	Pell (1994)	
Frenchman Cap dome	Mount Grace carbonatite	**MGC**	**51°31'20.56", 118°48'40.63"**					Extrusive; pyroclastic
		BL-081-3	51°35'30.45", 118°48'23.45"	359.3 ±2	Zircon (weighted average)	Igneous age	Millonig et al. (2012)	
		BL-081-3		50.9 ±0.8	Pyrochlore (weighted average)	Metamorphic age	Millonig et al. (2013)	
		RS-3	51°35'08.32", 118°48'23.18"	55 ±5	Zircon	Metamorphic age	Parrish (1995)	
		Unnamed	51°31'20.56", 118°48'40.63"	60	Pyrochlore	Metamorphic age	Pell (1994)	
	Three Valley gap carbonatite	**TVG-C**	**50°55'37.36", 118°23'31.47"**					
		PCA-303	50°55'49.20", 118°23'30.16"	359 +46/-43	Zircon (upper intercept)	Igneous age	Parrish (1995)	
				86 +12/-14	Zircon (lower intercept)	Metamorphic age		
		Unnamed	50°55'34", 118°23'29"	70–100	Zircon	Metamorphic age	Pell (1994)	
	Three Valley gap syenite	**TVG-S**	**50°55'37.36", 118°23'31.47"**					

a calciocarbonatite and consists of calcite (60–70 vol. %), biotite (10–20 vol. %), amphibole (hornblende, 5–20 vol. %), apatite (5–10 vol. %) and augite (1–5 vol. %), as well as trace amounts of titanite, ilmenite, pyrochlore, pyrrhotite, monazite, epidote (allanite), kyanite, REE-carbonates and zircon. Sample TVG-S (Table 1) is a nepheline syenite and consists of K-feldspar (50–60 vol. %), plagioclase (40–50 vol. %), augite (5–15 vol. %) and titanite (1–2 vol. %).

Preliminary Data Interpretation

Interpretation of the initial data has revealed key insights into the magmatic history of Late Devonian–Early Mississippian carbonatites and syenites in the southeastern Canadian Cordillera. Results from preliminary zircon U-Pb dating suggest that these rocks may record a significant magmatic pulse ca. 360 Ma. This aligns with a regional pulse of alkaline magmatism that affected the FCD and BRA ca. 360–340 Ma (Pell, 1994; Millonig et al., 2012; Millonig and Groat, 2013). While several carbonatite and syenite complexes in the BRA have been found to date from the Late Devonian–Early Mississippian (Figure 1b), the MGC and TVG carbonatite and syenite are the only known occurrences of this age in the Monashee Complex (Figure 1b). This period corresponds to a significant tectonic transition along the western Laurentian continental margin, which occurred ca. 390 Ma (Monger and Price, 2002). The tectonomagmatic setting is displayed schematically in Figure 2 (see Abdale et al., 2024, Figure 9). During this time, the margin shifted from an intraplate continental margin to an interplate convergent margin, followed by extensional tectonics along rejuvenated crustal faults and back-arc basin formation due to slab rollback further west during the Late Devonian to early Carboniferous (Figure 2; Roback et al., 1994; Smith et al., 1995; Colpron et al., 2007; Nelson and Colpron, 2007; Lund, 2008; Lund et al., 2010). In this tectonic setting, carbonatites likely intruded near the continental margin, where a thin continental lithosphere was present (Figure 2; Millonig et al., 2012; Abdale et al., 2024). Protoliths to the BRA carbonatite-syenite hostrocks (the Horsethief Creek Group) represent relatively deep-water, likely back-arc basin strata (Brown et al., 1986; Journeay, 1986; Scammell and Brown, 1990), whereas the FCD carbonatite-syenite hostrocks (the Monashee cover gneiss) represent shallow-water, continental-margin sediments (Figure 2; Wheeler, 1965; Reesor and Moore, 1971;

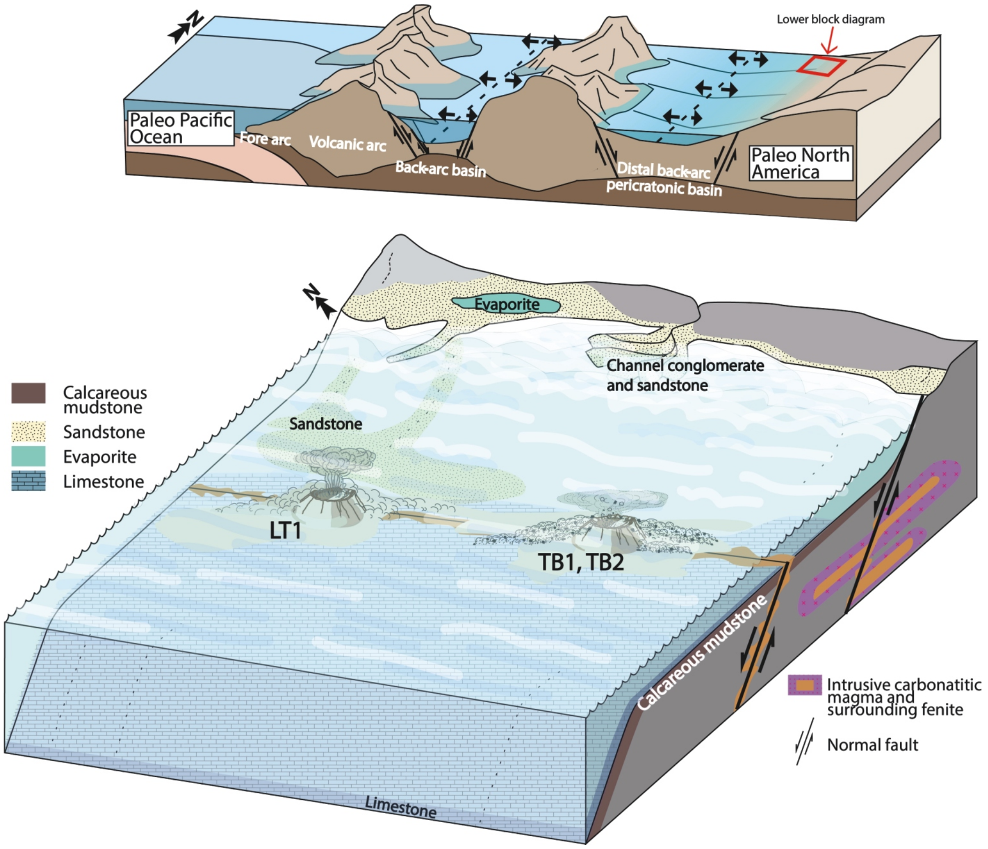


Figure 2. Schematic diagram of ancestral North American margin in Devonian–Mississippian times. Top panel shows a hypothetical depositional setting with extensional arrows and the location (small red box) of the bottom panel that shows the depositional mechanism of Mount Grace carbonatite lapilli tuff (LT1) and tuff breccia (TB1 and TB2) lithofacies as well as the calcareous mud, sandstone, evaporite and limestone in a transgressive marine sequence (modified from Abdale et al., 2024, Figure 9).

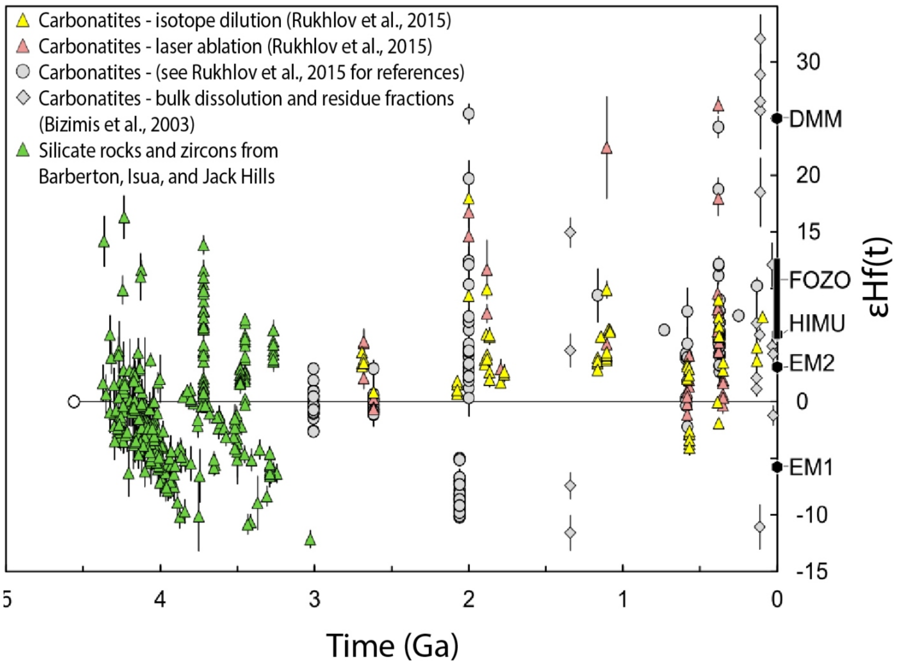


Figure 3. Hafnium evolution diagrams for carbonatites worldwide and late Archean syenitic complexes from the Canadian Shield (adapted from Rukhlov et al., 2015, Figure 5b). Depleted mid-ocean–ridge basalt (MORB) mantle (DMM), enriched mantle 1 and 2 (EM1, EM2), 'Focus zone' (FOZO) and high-^{238}U/^{204}Pb or (HIMU) mantle components are shown on the y-axis of this Hf(t) versus time (Ga) diagram; Hf(t) = ([^{176}Hf/^{177}Hf$_{(sample)}$/^{176}Hf/^{177}Hf$_{(CHUR)}$]-1) 10^{4}, where ^{176}Hf/^{177}Hf$_{(sample)}$ is the initial ratio in the sample and ^{176}Hf/^{177}Hf$_{(CHUR)}$ is the ratio in the chondritic uniform reservoir (CHUR) at that time (Rukhlov et al., 2015). Also shown are data from the oldest silicate rocks and detrital zircons from South Africa, Western Australia and West Greenland (Rukhlov et al., 2015). Error bars are 2 uncertainties that include propagated errors associated with age, measured ^{167}Lu/^{177}Hf and ^{176}Hf/^{177}Hf ratios, ^{176}Lu decay constant, and CHUR parameters. Copyright Province of British Columbia. All rights reserved. Used with permission.

Journeay, 1986; Scammell and Brown, 1990; Crowley, 1997; Höy, 2001). The abundance of Late Devonian–Early Mississippian alkaline rocks in the BRA reflects the thin lithosphere and concentration of reactivated deep-seated crustal faults within the back-arc basin, whereas further east on the continent, the thick crust and fewer faults may have limited such ultra-low viscosity intrusions (Figure 2).

Preliminary U-Pb and Hf isotopic data indicate correlations with mantle source characteristics, suggesting HIMU-EM2–like components that are consistent with metasomatized mantle sources. This is similar to the findings of Ruhklov et al. (2015), who presented Sr, Pb, Nd and Hf isotopic data for carbonatite occurrences mainly from the northern hemisphere, including a few samples from the Canadian Cordillera, along with published global data (Figure 3). Figure 3 presents carbonatite-evolution data, including HIMU (high-μ, where $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}[t = 0]$); a radiogenic Pb source found in MORBs, OIBs, kimberlites and carbonatites associated with recycled oceanic and continental crust subducted into the mantle (Hofmann and White, 1982; Zindler and Hart, 1986; Hofmann, 1997; Stracke et al., 2005); and EM2, a radiogenic Hf source formed from metasomatic enrichment of ancient oceanic lithosphere followed by long-term, deep-mantle storage (Zindler et al., 1979 and Roden et al., 1984; Workman et al., 2004). These signatures are consistent with a subduction zone, back-arc, thin-lithosphere setting. Results from this study establish the presence of a metasomatized mantle below the western continental margin in the Late Devonian–Early Mississippian (Figure 3). These initial observations will be explored further in future studies to better define the role of mantle heterogeneity in these magmatic systems.

Summary and Next Steps

Future research will focus on providing a comprehensive analysis of these findings, with implications for understanding mantle metasomatism and tectonic-magmatic interactions along continental margins. The successful application of zircon U-Pb geochronology and Hf isotopic analysis in this study demonstrates a robust methodology for understanding the magmatic history and mantle processes beneath western North America. These initial data hint at connections between regional tectonic shifts and magmatic processes; however, further studies are essential to fully elucidate how mantle dynamics and crustal structure influenced magmatism in this back-arc setting. Moving forward, additional data will be collected from approximately ten samples of carbonatites and syenites sourced from the FCD and BRA, with ages ranging from 800 to 360 Ma. Zircon Hf isotopic analysis of these samples will assist in further elucidating the Hf composition of the subcontinental mantle, thus enhancing understanding of its evolution and the tectonic context of the region. This expanded dataset will contribute to a more comprehensive interpretation of subcontinental mantle dynamics and the geochemical signatures associated with alkaline magmatism in this area. The results presented in this paper establish a preliminary framework, laying the groundwork for future detailed analyses on the interaction between mantle heterogeneity and tectonics in the Cordillera.

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References

Abdale, L., Russell, J.K. and Groat, L.A. (2024): The volcanic architecture and tectono-magmatic framework of the Mount Grace carbonatites, southeastern Canadian Cordillera; Canadian Journal of Earth Sciences, v. 61, no. 9, p. 985–1013, URL <https://doi.org/10.1139/cjes-2024-0001>.

Bell, K. and Tilton, G.R. (2001): Nd, Pb and Sr isotopic compositions of East African carbonatites: evidence for mantle mixing and plume inhomogeneity; Journal of Petrology, v. 42, no. 10, p. 1927–1946, URL <https://doi.org/10.1093/petrology/42.10.1927>.

Bell, K., Kjarsgaard, B.A. and Simonetti, A. (1999): Carbonatites—into the twenty-first century; Journal of Petrology, v. 39, p. 11–12.

Bizimis, M., Salters, V.J. and Dawson, J.B. (2003): The brevity of carbonatite sources in the mantle: evidence from Hf isotopes; Contributions to Mineralogy and Petrology, v. 145, p. 281–300.

Brown, R.L. (1978): Structural evolution of the southeast Canadian Cordillera: a new hypothesis; Tectonophysics, v. 48, no. 1–2, p. 133–151.

Brown, R.L. and Read, P.B. (1983): Shuswap terrane of British Columbia: a Mesozoic “core complex”; Geology, v. 11, no. 3, p. 164–168, URL <https://doi.org/10.1130/0091-7613(1983)11<164:STOBCA>2.0.CO;2>.

Brown, R.L., Journeay, J.M., Lane, L.S., Murphy, D.C. and Rees, C.J. (1986): Obduction, backfolding and piggy-back thrusting in the metamorphic hinterland of the southeastern Canadian Cordillera; Journal of Structural Geology, v. 8, no. 3–4, p. 255–268, URL <https://doi.org/10.1016/0191-8141(86)90047-7>.

Colpron, M., Logan, J.M. and Mortensen, J.K. (2002): U–Pb zircon age constraint for late Neoproterozoic rifting and initiation of the lower Paleozoic passive margin of western Laurentia; Canadian Journal of Earth Sciences, v. 39, p. 133–143.

Colpron, M., Nelson, J. and Murphy, D. (2007): Northern Cordilleran terranes and their interactions through time; GSA Today, v. 17, no. 4–5, p. 4–10, URL <https://doi.org / 10.1130/GSAT01704-5A.1>.

Crowley, J.L. (1997): U-Pb geochronologic constraints on the cover sequence of the Monashee complex, Canadian Cordillera: Paleoproterozoic deposition on basement; Canadian Journal of Earth Sciences, v. 34, no. 7, p. 1008–1022, URL <https://doi.org/10.1139/e17-083>.

Digel, S.G., Ghent, E.D., Carr, S.D. and Simony, P.S. (1998): Early Cretaceous kyanite-sillimanite metamorphism and Paleocene sillimanite overprint near Mount Cheadle, southeastern British Columbia: geometry, geochronology, and metamorphic implications; Canadian Journal of Earth Sciences, v. 35, no. 9, p. 1070–1087, URL <https://doi.org/10.1139/e98-052>.

Ewing, T.E. (1981): Paleogene tectonic evolution of the Pacific Northwest; Journal of Geology, v. 88, p. 619–638.

Gerdes, A. and Zeh, A. (2006): Combined U–Pb and Hf isotope LA-(MC-)ICP-MS analyses of detrital zircons: comparison with SHRIMP and new constraints for the provenance and age of an Armorican metasediment in Central Germany; Earth and Planetary Science Letters, v. 249, no. 1–2, p. 47–61, URL <https://doi.org/10.1016/j.epsl.2006.06.039>.

Gerdes, A. and Zeh, A. (2009): Zircon formation versus zircon alteration—new insights from combined U–Pb and Lu–Hf in-situ LA-ICP-MS analyses, and consequences for the interpretation of Archean zircon from the Central Zone of the Limpopo Belt; Chemical Geology, v. 261, no. 3–4, p. 230–243, URL <https://doi.org/10.1016/j.chemgeo.2008.03.005>.

Gibson, H.D., Brown, R.L. and Carr, S.D. (2008): Tectonic evolution of the Selkirk fan, southeastern Canadian Cordillera: a composite Middle Jurassic–Cretaceous orogenic structure; Tectonics, v. 27, no. 6, p. 1–14, URL <https://doi.org/10.1029/2007TC002160>.

Hofmann, A.W. (1997): Mantle geochemistry: the message from oceanic magmatism; Nature, v. 385, p. 219–229.

Hofmann, A.W. and White, W.M. (1982): Mantle plumes from ancient oceanic crust; Earth and Planetary Science Letters, v. 57, no. 2, p. 421–436, URL <https://doi.org/10.1016/0012-821X(82)90161-3>.

Höy, T. (1987): Geology of the Cottonbelt lead-zinc-magnetite layer, carbonatites and alkalic rocks in the Mount Grace area, Frenchman Cap dome, southeastern British Columbia; BC Ministry of Energy, Mines and Low Carbon Innovation, Bulletin 80, 99 p., URL <https://cmscontent.nrs.gov.bc.ca/geoscience/PublicationCatalogue/GeoFile/BCGS_GF2002-04.pdf> [November 2024].

Höy, T. (2001): Sedex and Broken Hill-type deposits, northern Monashee Mountains, southern British Columbia; *in* Geological Fieldwork 2000, BC Ministry of Energy, Mines and Low Carbon Innovation, BC Geological Survey, Paper 2001-01, p. 85–114.

Höy T. and McMillan, W.J. (1979): Geology in the vicinity of Frenchman Cap gneiss dome, BC; *in* Geological Fieldwork 1978, BC Ministry of Energy, Mines and Low Carbon Innovation, Paper 1979-1, p. 25–30, URL <https://cmscontent.nrs.gov.bc.ca/geoscience/publicationcatalogue/Paper/BCGS_P1979-01.pdf#page=24> [November 2024].

Journeay, J.M. (1986): Stratigraphy, internal strain and tectonometamorphic evolution of northern Frenchman Cap dome: an exhumed duplex structure, Omineca hinterland, S.E. Canadian Cordillera; Ph.D. thesis, Queen's University, 522 p.

Lund, K. (2008): Geometry of the Neoproterozoic and Paleozoic rift margin of western Laurentia: implications for mineral deposit settings; Geosphere, v. 4, no. 2, p. 429–444, URL <https://doi.org/10.1130/GES00121.1>.

Lund, K., Aleinikoff, J.N., Evans, K.V., duBray, E.A., Dewitt, E.H. and Unruh, D.M. (2010): SHRIMP U-Pb dating of recurrent Cryogenian and Late Cambrian–Early Ordovician alkalic magmatism in central Idaho: implications for Rodinian rift tectonics; Geological Society of America Bulletin, v. 122, no. 3–4, p. 430–453, URL <https://doi.org/10.1130/B26565.1>.

McMillan, N.J. and McLemore, V.T. (2004): Cambrian–Ordovician magmatism and extension in New Mexico and Colorado. Bulletin; New Mexico Bureau of Geology and Mineral Resources, v. 160, p. 1–11.

Millonig, L.J. and Groat, L.A. (2013): Carbonatites in western North America–occurrences and metallogeny; *in* Tectonics, Metallogeny, and Discovery: The North American Cordillera and Similar Accretionary Settings, M. Colpron, T. Bissig, B.G. Rusk and J.F.H. Thompson (ed.), Society of Economic Geologists, v. 17, p. 245–264, URL <https://doi.org/10.5382/sp.17.07>.

Millonig, L.J., Gerdes, A. and Groat, L.A. (2012): U-Th-Pb geochronology of meta-carbonatites and meta-alkaline rocks in the southern Canadian Cordillera: a geodynamic perspective; Lithos, v. 152, p. 202–217, URL <https://doi.org/10.1016/j.lithos.2012.06.016>.

Mitchell, R.H. (2005): Carbonatites and carbonatites and carbonatites; Canadian Mineralogist, v. 43, no. 6, p. 2049–2068, URL <https://doi.org/10.2113/gscanmin.43.6.2049>.

Monger, J. and Price, R.A. (2002): The Canadian Cordillera: geology and tectonic evolution; CSEG Recorder, v. 27, p. 17–36.

Monger, J.W.H., Price, R.A. and Tempelman-Kluit, D.J. (1982): Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera; Geology, v. 10, no. 2, p. 70–75, URL <https://doi.org/10.1130/0091-7613(1982)10<70:TAATOO>2.0.CO;2>.

Nelson, J. and Colpron, M. (2007): Tectonics and metallogeny of the British Columbia, Yukon and Alaskan Cordillera, 1.8 Ga to the present; *in* Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, W.D. Goodfellow (ed.), Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 755–791.

Okulitch, A.V. (1984): The role of the Shuswap metamorphic complex in Cordilleran tectonism: a review; Canadian Journal of Earth Sciences, v. 21, no. 10, p. 1171–1193, URL <https://doi.org/10.1139/e84-123>.

Parrish, R.R. (1995): Thermal evolution of the southeastern Canadian Cordillera; Canadian Journal of Earth Sciences, v. 32, no. 10, p. 1618–1642, URL <https://doi.org/10.1139/e95-130>.

Parrish, R.R. and Scammell, R.J. (1988): The age of the Mount Copeland Syenite Gneiss and its metamorphic zircons, Monashee Complex, southeastern British Columbia; *in* Radiogenic Age and Isotopic Studies, Report 2, Geological Survey of Canada, Paper 88-2, p. 21–28, URL <https://doi.org/10.4095/126597>.

Pell, J. (1994): Carbonatites, nepheline syenites, kimberlites and related rocks in British Columbia; BC Ministry of Energy, Mines and Low Carbon Innovation, Bulletin 88, 144 p.

Perkins, M.J. (1983): Structural geology and stratigraphy, Big Bend of the Columbia River, Selkirk Mountains, British Columbia; Ph.D. thesis, Carleton University, 238 p.

Rankin, A. (2005): Carbonatite-associated rare metal deposits: composition and evolution of ore-forming fluids–the fluid inclusion evidence; *in* Rare Metal Geochemistry and Ore Deposits, R.L. Linnen and I.M. Samson (ed.), Geological Association of Canada, Short Course Notes 17, p. 299–314.

Read, P.B. and Brown, R.L. (1981): Columbia River fault zone: southeastern margin of the Shuswap and Monashee complexes, southern British Columbia; Canadian Journal of Earth Sciences, v. 18, no. 7, p. 1127–1145.

Reesor, J.E. and Moore, J.M., Jr. (1971): Petrology and structure of Thor-Odin gneiss dome, Shuswap metamorphic complex, British Columbia; Geological Survey of Canada, Bulletin 195, 149 p.

Roback, R.C., Sevigny, J.H. and Walker, N.W. (1994): Tectonic setting of the Slide Mountain terrane, southern British Columbia; Tectonics, v. 13, no. 5, p. 1242–1258.

Roden, M.F., Frey, F.A and Francis, D.M. (1984): An example of consequent mantle metasomatism in peridotite inclusions from Nunivak Island, Alaska; Journal of Petrology, v. 25, no. 2, p. 546–577.

Rukhlov, A.S., Bell, K. and Amelin, Y. (2015): Carbonatites, isotopes and evolution of the subcontinental mantle: an overview; *in* Symposium on Strategic and Critical Materials Proceedings, G.J. Simandl and M. Neetz, BC Ministry of Energy, Mines and Low Carbon Innovation, BC Geological Survey, Paper 2015-3, p. 39–64, URL <https://cmscontent.nrs.gov.bc.ca/geoscience/PublicationCatalogue/Paper/BCGS_P2015-03-06_Rukhlov.pdf> [November 2024].

Scammell, R.J. and Brown, R.L. (1990): Cover gneisses of the Monashee Terrane: a record of synsedimentary rifting in the North American Cordillera; Canadian Journal of Earth Sciences, v. 27, no. 5, p. 712–726, URL <https://doi.org/10.1139/e90-070>.

Simandl, G.J. and Paradis, S. (2018): Carbonatites: related ore deposits, resources, footprint, and exploration methods; Applied Earth Science, v. 127, no. 4, p. 123–152, URL <https://doi.org/10.1080/25726838.2018.1516935>.

Smith, A.D., Brandon, A.D. and Lambert, R.StJ. (1995): Nd-Sr isotope systematics of Nicola Group volcanic rocks, Quesnel terrane; Canadian Journal of Earth Sciences, v. 32, no. 4, p. 437–446, URL <https://doi.org/10.1139/e95-037>.

Stracke, A., Hofmann, A.W. and Hart, S.R. (2005): FOZO, HIMU, and the rest of the mantle zoo; Geochemistry, Geophysics, Geosystems, v. 6, no. 5, 20 p., URL <https://doi.org/10.1029/2004GC000824>.

Struik, L.C. (1993): Intersecting intracontinental Tertiary transform fault systems in the North American Cordillera; Canadian Journal of Earth Sciences, v. 30, no. 6, p. 1262–1274, URL <https://doi.org/10.1139/e93-108>.

Veevers, J.J. (2007): Pan-Gondwanaland post-collisional extension marked by 650–500 Ma alkaline rocks and carbonatites and related detrital zircons: a review; Earth-Science Reviews, v. 83, no. 1–2, p. 1–47.

Wheeler, J.O. (1965): Big Bend map-area, British Columbia, 82M (east half); Geological Survey of Canada, Paper 64–32, 37 p., URL <https://doi.org/10.4095/101007>.

Woolley, A.R. and Bailey, D.K. (2012): The crucial role of lithospheric structure in the generation and release of carbonatites: geological evidence; Mineralogical Magazine, v. 76, no. 2, p. 259–270, URL <https://doi.org/10.1180/minmag.2012.076.2.02>.

Woolley, A.R. and Kjarsgaard, B.A. (2008): Carbonatite occurrences of the world: map and database; Geological Survey of Canada, Open File 5796, 28 p., URL <https://doi.org/10.4095/225115>.

Workman, R.K., Hart, S.R., Jackson, M., Regelous, M., Farley, K.A., Blusztajn, J., Kurz, M. and Staudigel, H. (2004): Recycled metasomatized lithosphere as the origin of the Enriched Mantle II (EM2) end-member: evidence from the Samoan Volcanic Chain; Geochemistry, Geophysics, Geosystems, v. 5, no. 4, p. 1–44, URL <https://doi.org/10.1029/2003GC000623>.

Zindler, A. and Hart, S.R. (1986): Chemical geodynamics; Annual Review of Earth and Planetary Science Letters, v. 14, p. 493–571.

Zindler, A., Hart, S.R., Frey, F.A. and Jakobsson, S.P. (1979): Nd and Sr isotope ratios and rare earth element abundances in Reykjanes Peninsula basalts: evidence for mantle heterogeneity beneath Iceland; Earth and Planetary Science Letters, v. 45, p. 249–262.