Are Cordilleran carbonatite hosts of Ta, Nb and REE from the deep mantle?

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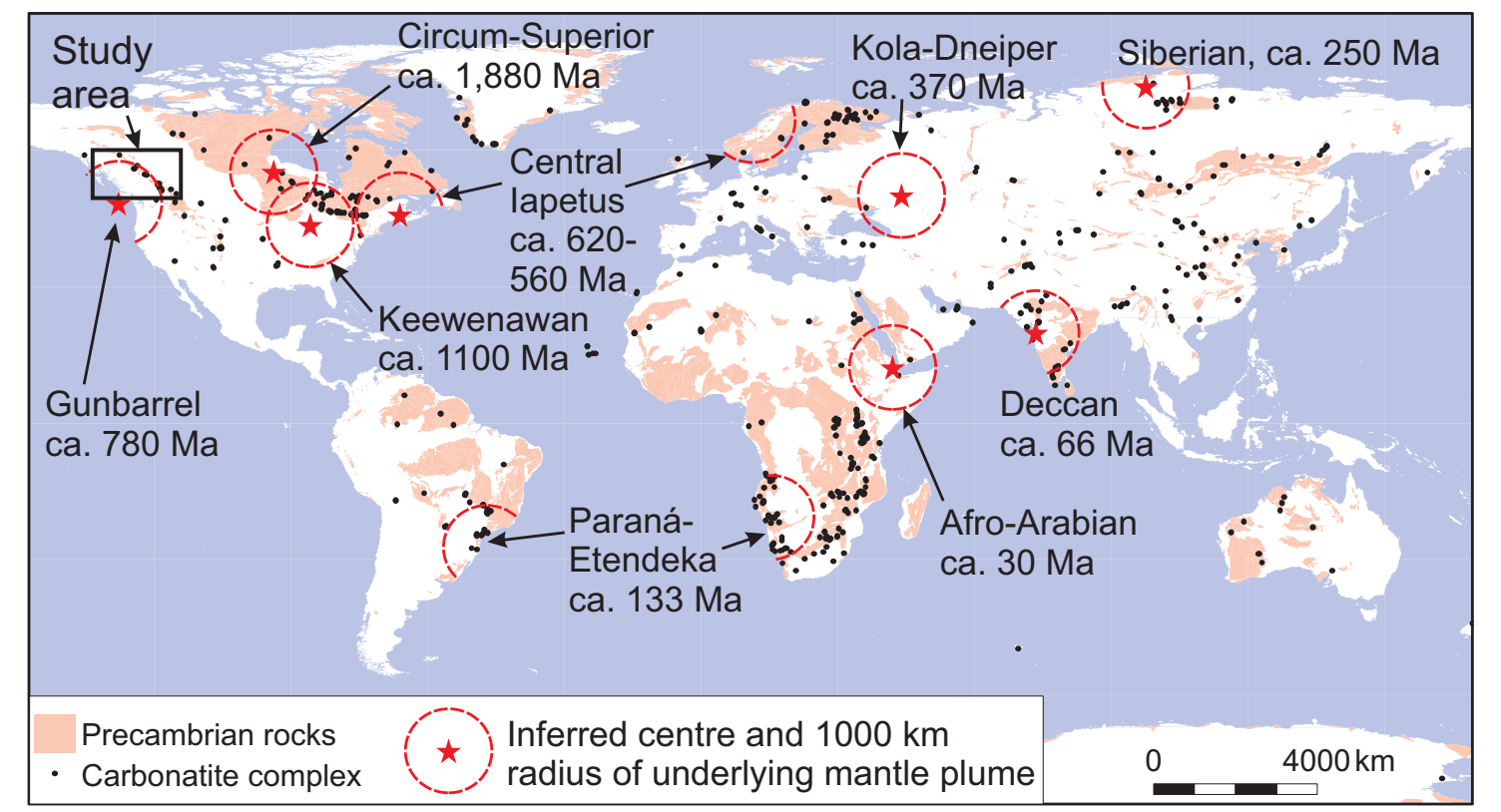
Introduction

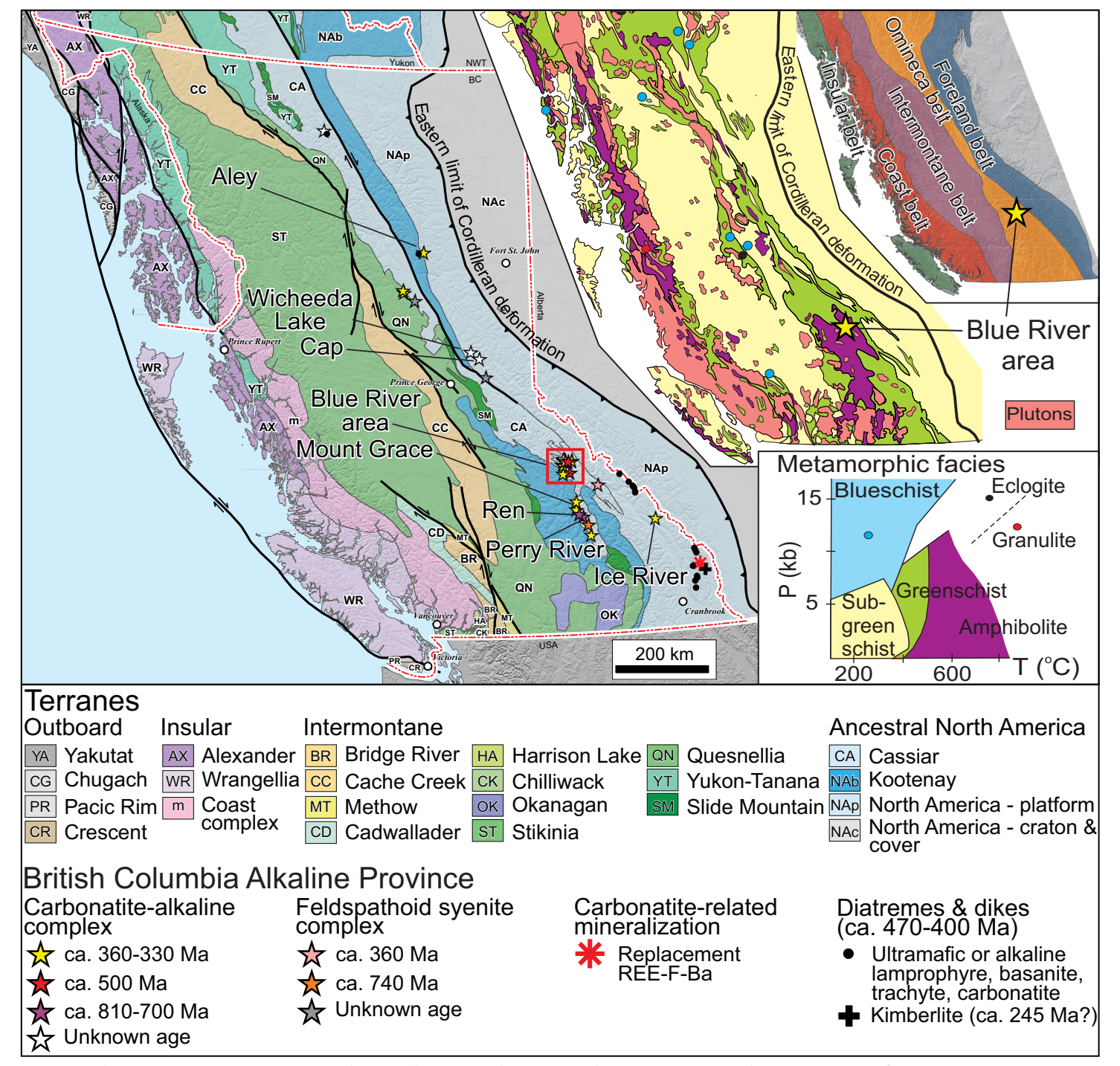
Carbonatites are important exploration targets for Ta, Nb, REE and other commodities. In the Canadian Cordillera, carbonatites were emplaced at ca. 810-700, 500, and 360-330 Ma, forming part of the British Columbia alkaline province. The most prolific Late Paleozoic carbonatites, hosting Nb-Ta and REE deposits, are unusual. In contrast to most carbonatites globally, which are found in intracratonic regions in association with flood basalts, they formed in a more active setting, along the western margin of Laurentia. We investigate metallogeny of these rocks.

Carbonatites and examples of related large igneous provinces (LIPs)


Study area
Circum-Superior ca. 1,880 Ma
Kola-Dneiper ca. 370 Ma
Siberian, ca. 250 Ma
Central Iapetus ca. 620-560 Ma
Keewenawan ca. 1100 Ma
Gunbarrel ca. 780 Ma
Deccan ca. 66 Ma
Paraná-Etendeka ca. 133 Ma
Afro-Arabian ca. 30 Ma
Precambrian rocks
Carbonatite complex
Inferred centre and 1000 km radius of underlying mantle plume
0 4000 km

Modified from Woolley & Kjarsgaard (2008), Ernst & Bell (2010), and Ernst & Bleeker (2010).

Carbonatite-alkaline complexes and dike-diatreme swarms defining the British Columbia Alkaline Province

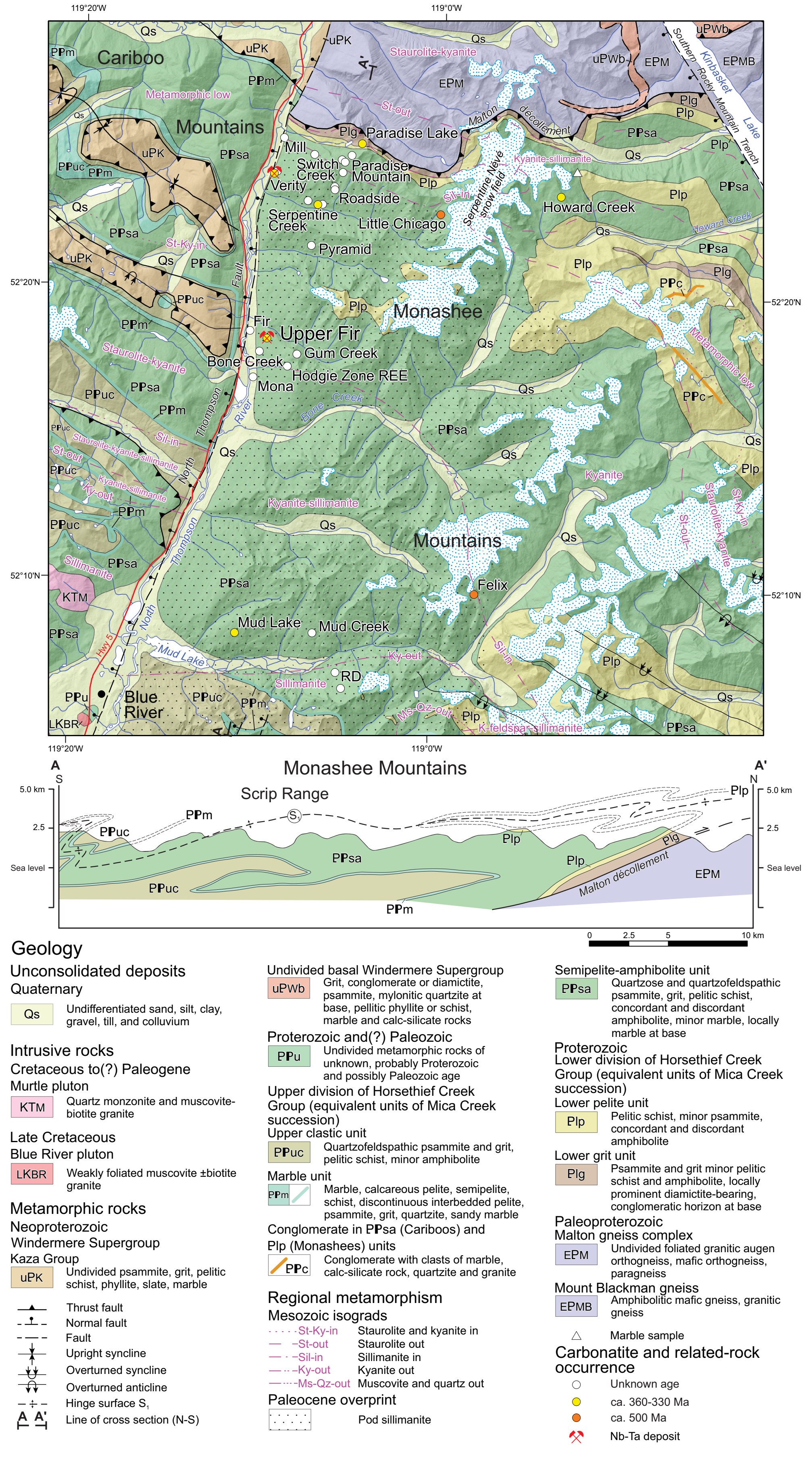

Aley
Wicheeda Lake
Cap
Blue River area
Mount Grace
Ren
Perry River
Ice River
Blue River area
Plutons
Eastern limit of Cordilleran deformation
Insular belt
Coast belt
Intermontane belt
Omineca belt
Foreland belt
200 km
Metamorphic facies
P (kb)
15
5
Blueschist
Eclogite
Granulite
Greenschist
Amphibolite
Sub-green schist
200
600
T (°C)
Terranes
Outboard
YA Yakutat
CG Chugach
PR Pacic Rim
CR Crescent
Insular
AX Alexander
WR Wrangellia
m Coast complex
Intermontane
BR Bridge River
CC Cache Creek
MT Methow
CD Cadwallader
HA Harrison Lake
CK Chilliwack
OK Okanagan
ST Stikinia
QN Quesnellia
YT Yukon-Tanana
SM Slide Mountain
Ancestral North America
CA Cassiar
NAb Kootenay
NAp North America - platform
NAc North America - craton & cover
British Columbia Alkaline Province
Carbonatite-alkaline complex
ca. 360-330 Ma
ca. 500 Ma
ca. 810-700 Ma
Unknown age
Feldspathoid syenite complex
ca. 360 Ma
ca. 740 Ma
Unknown age
Carbonatite-related mineralization
Replacement REE-F-Ba
Diatremes & dikes (ca. 470-400 Ma)
Ultramafic or alkaline lamprophyre, basanite, trachyte, carbonatite
Kimberlite (ca. 245 Ma?)

Carbonatite and related-rock complexes after Parrish & Scammell (1988), Pell (1994), Rukhlov & Bell (2010), Millonig & Groat (2013), and Rukhlov et al. (2018). Terrane geology after Nelson et al. (2013). Metamorphic and plutonic rocks after Monger & Hutchison (1971), Read et al. (1991), and Monger (2014). Morphogeological belts of the Canadian Cordillera after Gabrielse et al. (1991) and Hickin et al. (2017).

Blue River carbonatites

Carbonatites of the Blue River area underwent high-grade metamorphism and retrograde shearing during Cordilleran orogeny (Pell, 1994). They host two Ta-Nb deposits. Upper Fir is the largest and best-studied deposit, containing unusual, Ta-rich pyrochlore and ferrocolumbite, with minor fersmite and other Nb minerals, associated with locally coarse molybdenite (Rukhlov et al., 2018).

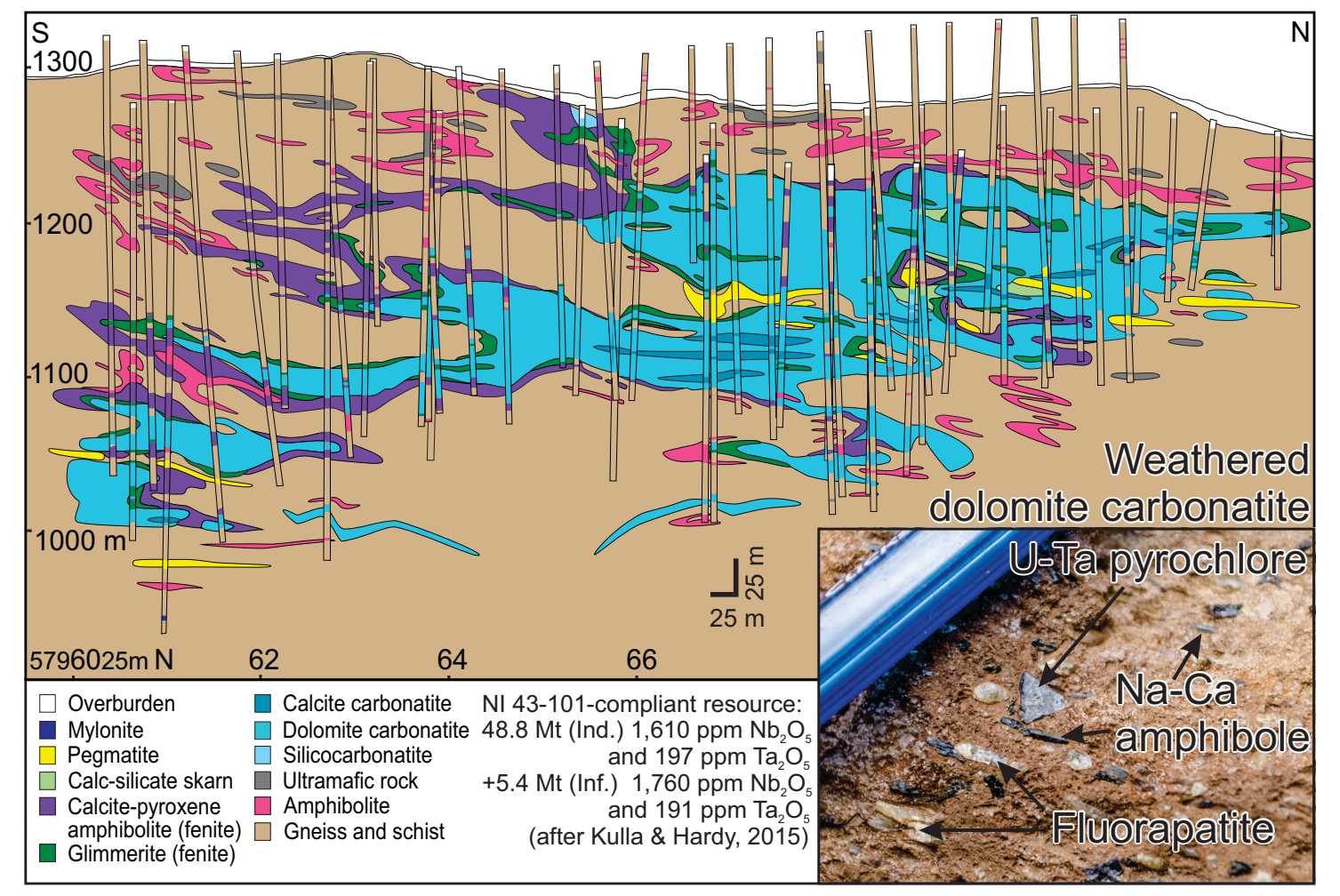
Carbonatites and related rocks of the Blue River area


119°20'W
119°0'W
52°20'N
52°10'N
Cariboo
Mountains
Paradise Lake
Mill
Switch Creek
Paradise Mountain
Verity
Roadside
Serpentine Creek
Little Chicago
Pyramid
Howard Creek
Monashee
Upper Fir
Gum Creek
Bone Creek
Hodgie Zone REE
Mona
Fir
Mountains
Felix
Mud Lake
Mud Creek
RD
Blue River
North Thompson River
Fault
Southern Rocky Mountain Trench
Kinbasket Lake
Malton décollement
Serpentine Névé snow field
Metamorphic low
Staurolite-kyanite
Kyanite-sillimanite
Sillimanite
K-feldspar-sillimanite
Hwy 5
A S
A' N
Monashee Mountains
Scrip Range
5.0 km
2.5
Sea level
0 2.5 5 10 km
Geology
Unconsolidated deposits
Quaternary
Qs Undifferentiated sand, silt, clay, gravel, till, and colluvium
Intrusive rocks
Cretaceous to(?) Paleogene
Murtle pluton
KTM Quartz monzonite and muscovite-biotite granite
Late Cretaceous
Blue River pluton
LKBR Weakly foliated muscovite ±biotite granite
Metamorphic rocks
Neoproterozoic
Windermere Supergroup
Kaza Group
uPK Undivided psammite, grit, pelitic schist, phyllite, slate, marble
Undivided basal Windermere Supergroup
uPWb Grit, conglomerate or diamictite, psammite, mylonitic quartzite at base, pellitic phyllite or schist, marble and calc-silicate rocks
Proterozoic and(?) Paleozoic
PPu Undivided metamorphic rocks of unknown, probably Proterozoic and possibly Paleozoic age
Upper division of Horsethief Creek Group (equivalent units of Mica Creek succession)
Upper clastic unit
PPuc Quartzofeldspathic psammite and grit, pelitic schist, minor amphibolite
Marble unit
PPm Marble, calcareous pelite, semipelite, schist, discontinuous interbedded pelite, psammite, grit, quartzite, sandy marble
Conglomerate in PPsa (Cariboos) and Plp (Monashees) units
PPc Conglomerate with clasts of marble, calc-silicate rock, quartzite and granite
Semipelite-amphibolite unit
PPsa Quartzose and quartzofeldspathic psammite, grit, pelitic schist, concordant and discordant amphibolite, minor marble, locally marble at base
Proterozoic
Lower division of Horsethief Creek Group (equivalent units of Mica Creek succession)
Lower pelite unit
Plp Pelitic schist, minor psammite, concordant and discordant amphibolite
Lower grit unit
Plg Psammite and grit minor pelitic schist and amphibolite, locally prominent diamictite-bearing, conglomeratic horizon at base
Paleoproterozoic
Malton gneiss complex
EPM Undivided foliated granitic augen orthogneiss, mafic orthogneiss, paragneiss
Mount Blackman gneiss
EPMB Amphibolitic mafic gneiss, granitic gneiss
Thrust fault
Normal fault
Fault
Upright syncline
Overturned syncline
Overturned anticline
Hinge surface S1
Line of cross section (N-S)
Regional metamorphism
Mesozoic isograds
St-Ky-in Staurolite and kyanite in
St-out Staurolite out
Sil-in Sillimanite in
Ky-out Kyanite out
Ms-Qz-out Muscovite and quartz out
Paleocene overprint
Pod sillimanite
△ Marble sample
Carbonatite and related-rock occurrence
○ Unknown age
● ca. 360-330 Ma
● ca. 500 Ma
Nb-Ta deposit

Carbonatite complexes after Pell (1994), Rukhlov & Bell (2010), Millonig et al. (2012, 2013), Millonig & Groat (2013), and Rukhlov et al. (2018). Geology and metamorphic isograds after Campbell (1968), Simony et al. (1980), Raeside & Simony (1983), Pell & Simony (1987), McDonough & Murphy (1990), McDonough et al. (1991a, b, 1992), Digel et al. (1998), and Murphy (2007).

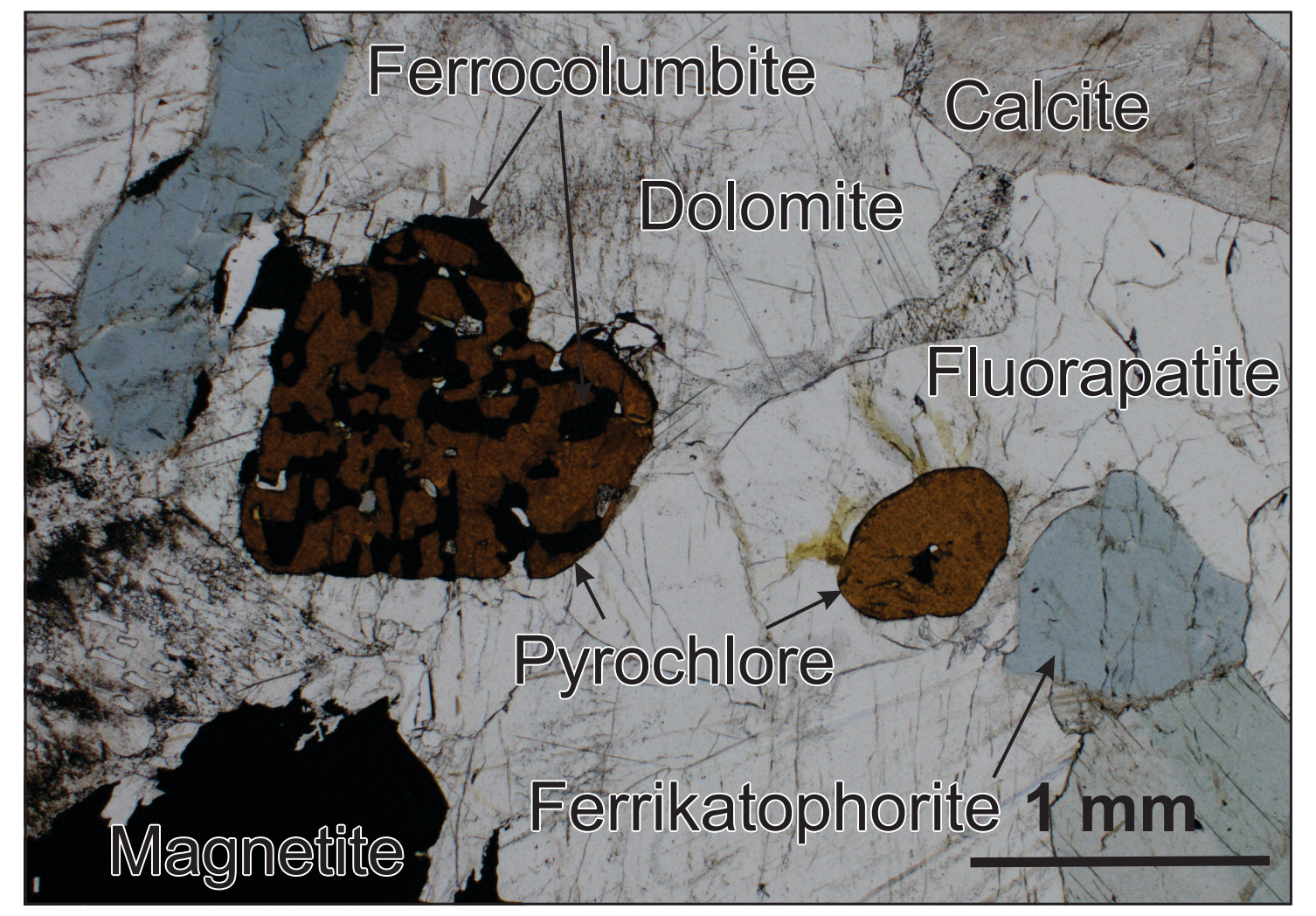
Upper Fir deposit

North-south geological cross-section through the Upper Fir carbonatite complex hosting an unusual Ta-Nb deposit, one of the largest in B.C.

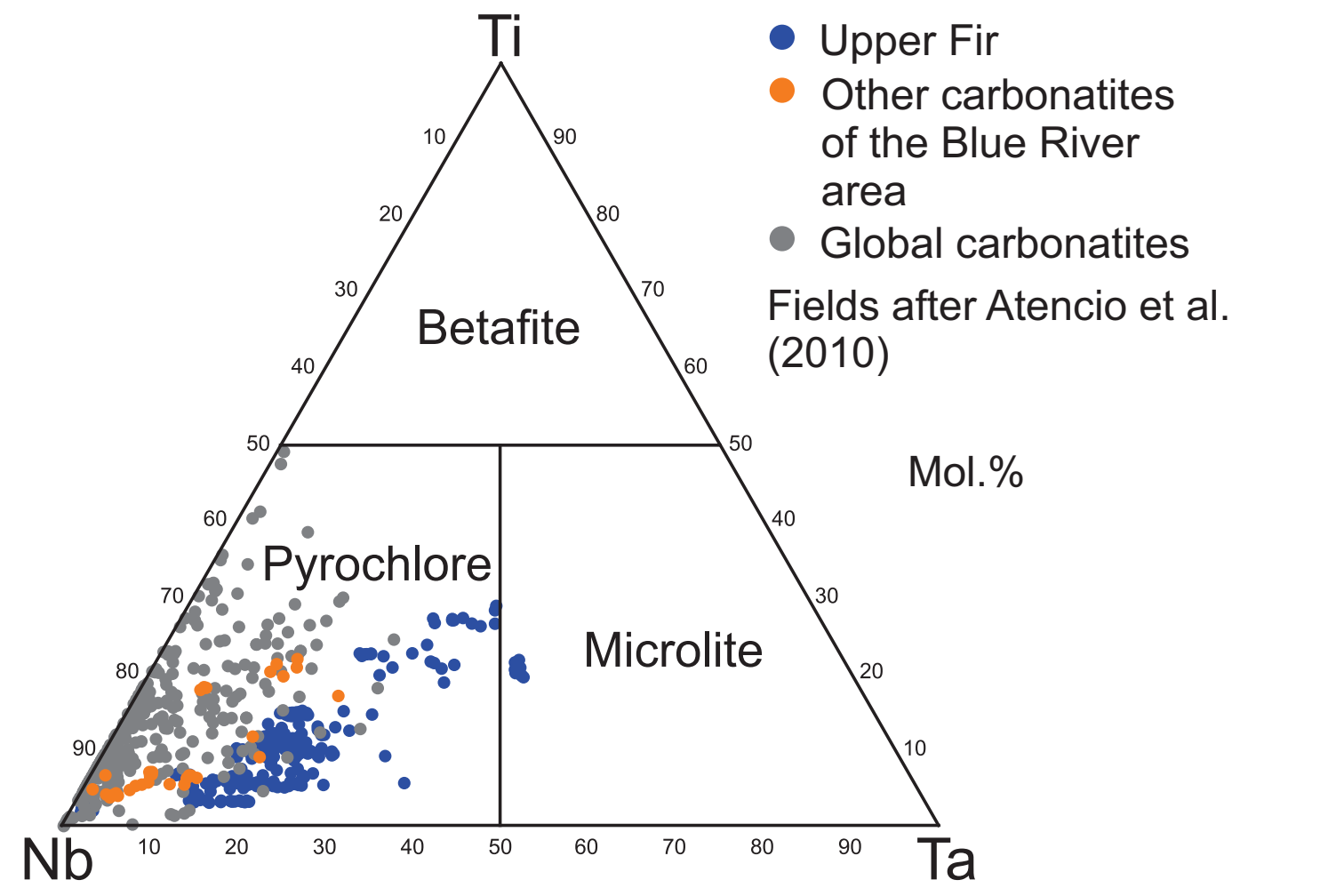

S
N
1300
1200
1100
1000 m
5796025m N
62
64
66
25 m
Weathered dolomite carbonatite
U-Ta pyrochlore
Na-Ca amphibole
Fluorapatite
Overburden
Mylonite
Pegmatite
Calc-silicate skarn
Calcite-pyroxene amphibolite (fenite)
Glimmerite (fenite)
Calcite carbonatite
Dolomite carbonatite
Silicocarbonatite
Ultramafic rock
Amphibolite
Gneiss and schist
NI 43-101-compliant resource:
48.8 Mt (Ind.) 1,610 ppm Nb_2O_5 and 197 ppm Ta_2O_5
+5.4 Mt (Inf.) 1,760 ppm Nb_2O_5 and 191 ppm Ta_2O_5
(after Kulla & Hardy, 2015)

Based on 3D view of drill-hole data (Commerce Resources Corp., pers. comm.) in 150 m wide corridor. Lithological logs are shown only for a 10 m wide corridor for clarity (after Rukhlov et al., 2018).

Example of Ta-Nb mineralization in carbonatites at Upper Fir


Ferrocolumbite
Calcite
Dolomite
Fluorapatite
Pyrochlore
Magnetite
Ferrikatophorite
1 mm

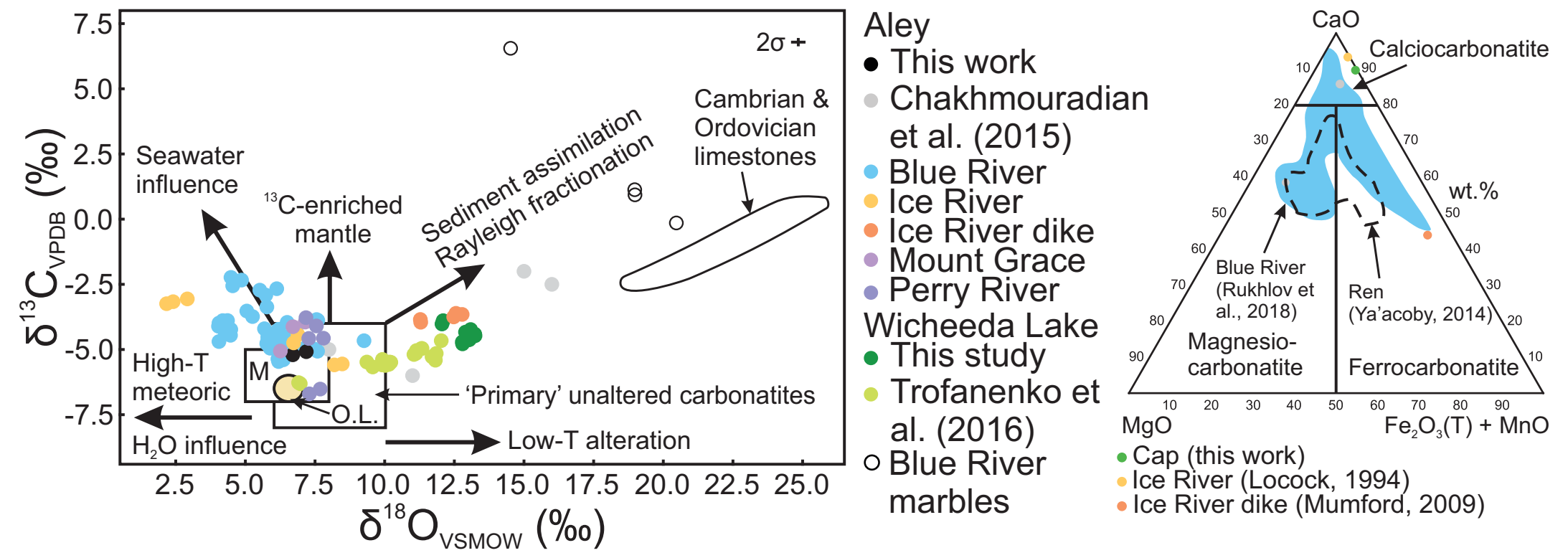
Plane-polarized light photomicrograph of granoblastic calcite-dolomite carbonatite containing Mg-Ta-rich ferrocolumbite replacing U-Ta-rich pyrochlore, Na-Ca amphibole (ferrikatophorite), fluorapatite, and Ti-bearing magnetite (after Rukhlov et al., 2018).



Ti-Nb-Ta plot for pyrochlore supergroup from Blue River carbonatites (after Rukhlov et al., 2018). Upper Fir pyrochlores are unusually Ta-rich.

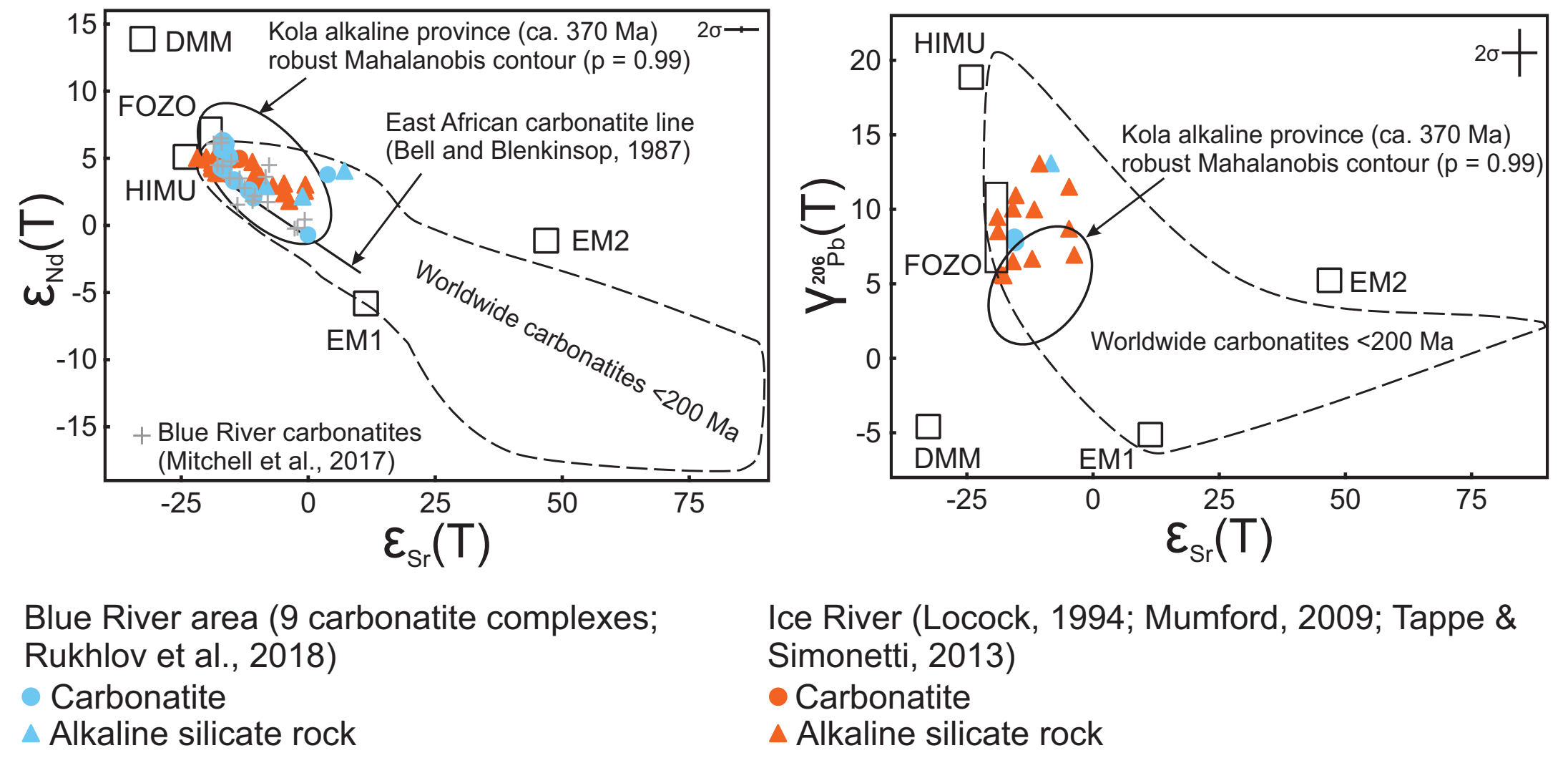
Geochemistry

$\delta^{18}O_{VSMOW}$ (‰) vs $\delta^{13}C_{VPDB}$ (‰) plot for separated calcite and dolomite from British Columbia carbonatites, related rocks, and sedimentary carbonates and CaO-MgO-[Fe_2O_3(T)+MnO] plot for the carbonatites



Arrows indicate processes causing shifts in $\delta^{18}O$ and $\delta^{13}C$ (after Demény et al., 2004 and references therein). Primary unaltered carbonatite field after Taylor et al. (1967), mantle (M) field after Deines (1989), fresh natrocarbonatite from Oldoinyo Lengai (O.L.) field after Keller & Hoefs (1995), and Cambrian and Ordovician limestone field after Veizer et al. (1999) and Chakhmouradian et al. (2015). Data from Blue River after Rukhlov et al. (2018). Most carbonatites retained their primary mantle signature despite high-grade metamorphism and deformation, which contrasts with the data from Aley, Wicheeda Lake, and Ice River Ba-REE-rich carbonatite dike.

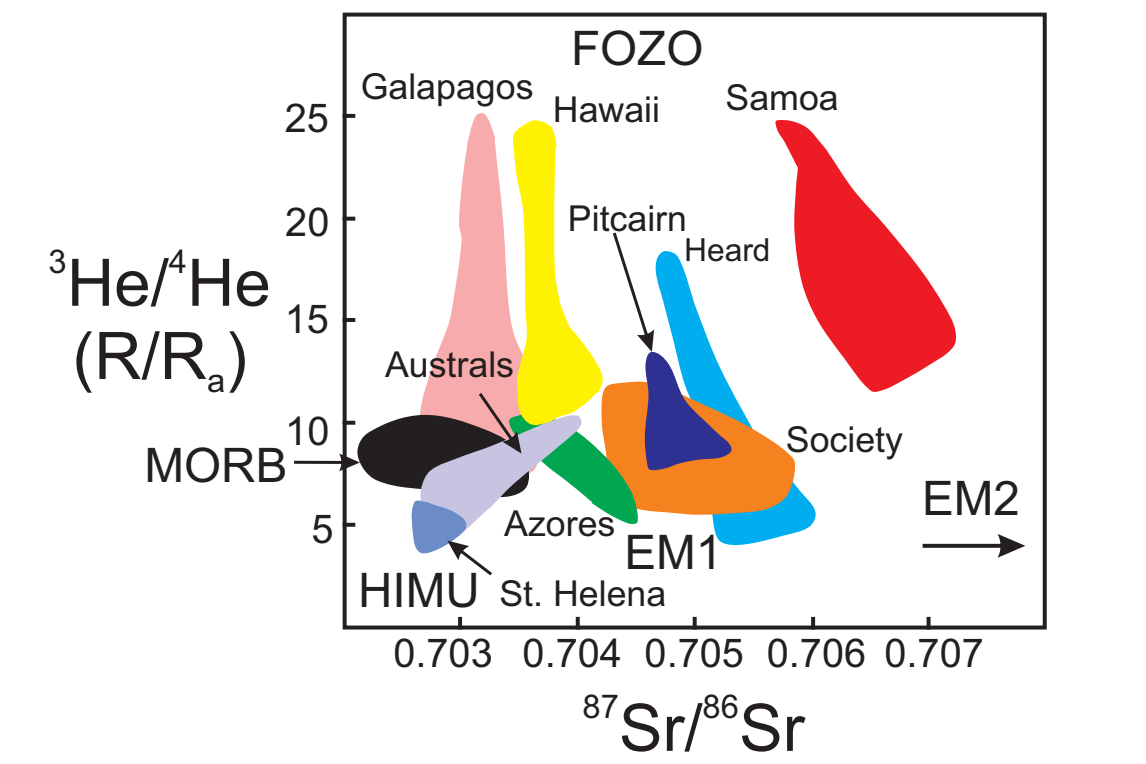
Sr-Pb-Nd isotope correlation diagrams for the 360-330 Ma carbonatites and related rocks of British Columbia



Data from the Blue River area are for separated calcite, dolomite and apatite fractions (after Rukhlov et al., 2018). Compiled data from Ice River are for both separated mineral and whole-rock fractions (Locock, 1994; Mumford, 2009; Tappe & Simonetti, 2013). Fields for the Kola alkaline province and the <200 Ma worldwide carbonatites from Rukhlov et al. (2015). Samples having extremely radiogenic Pb isotopic compositions due to re-equilibration with coexisting U-rich minerals during metamorphism are not shown on the ε_{Sr}(T) vs γ_{Pb}(T) diagram. The 360-330 Ma carbonatites and related rocks of the British Columbia alkaline province follow mixing trends involving FOZO (FOcus ZOne), HIMU (high-$^{238}U/^{204}Pb$ or μ), and EM1 (enriched mantle 1) mantle end-members found in oceanic basalts, young (<200 Ma) carbonatites worldwide, and the plume-related Kola alkaline province (ca. 370 Ma). FOZO, HIMU, EM1, and EM2 are considered to be the lower mantle components sampled by mantle plumes (e.g., Hart et al., 1992; Hofmann, 2014). Note that the depleted, mid-ocean ridge mantle (DMM) end-member, representing the upper mantle, is excluded from the mixing trends defined by the carbonatite data.

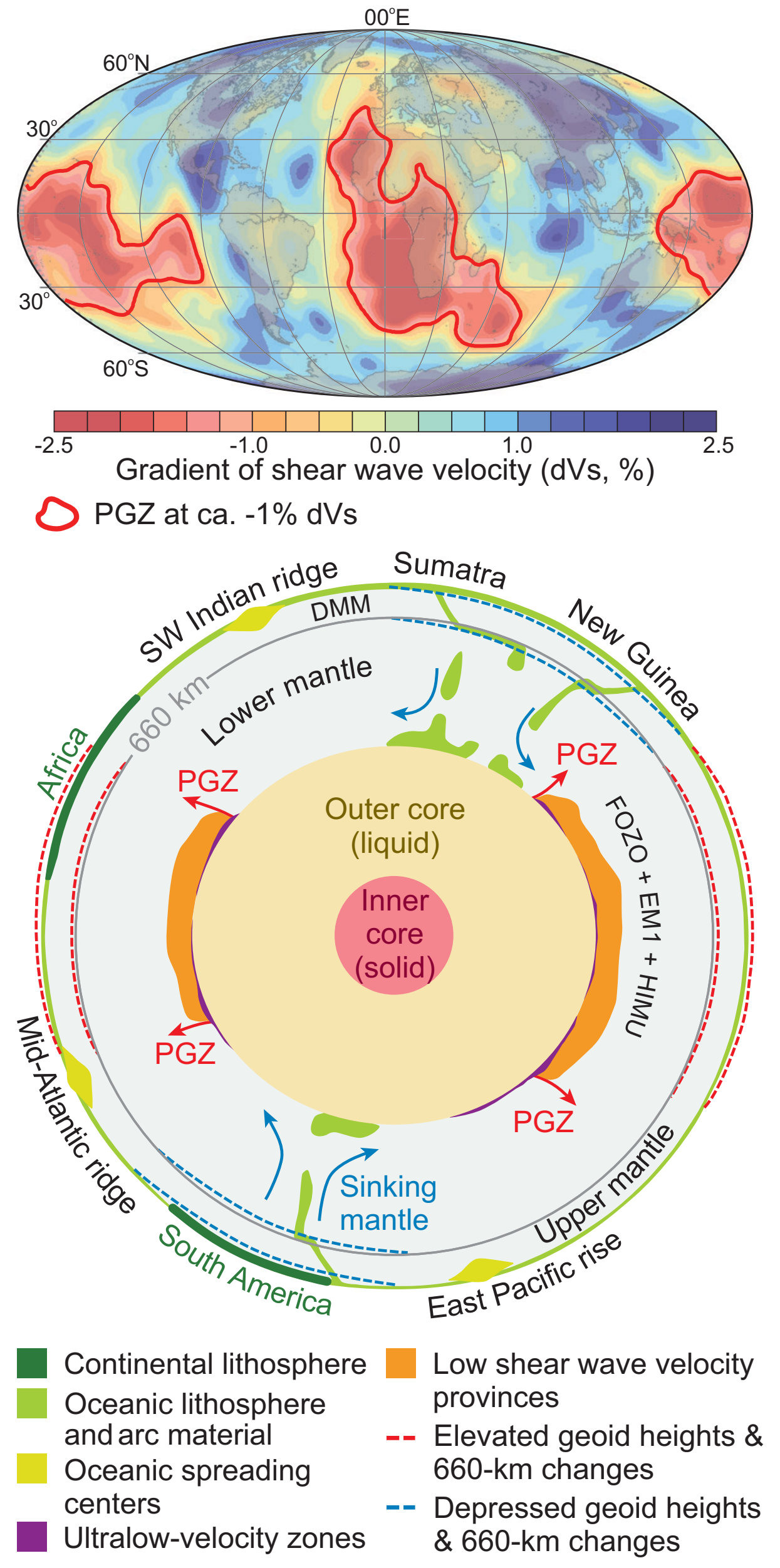
Mantle source

Sr vs He isotope correlation plot for oceanic basalts (from Keken et al., 2002)



The data from OIBs define elongated mixing arrays converging on the FOZO component at high $^3He/^4He$ ratios, indicating relatively undegassed, i.e. deep-seated source of the hotspot lavas.

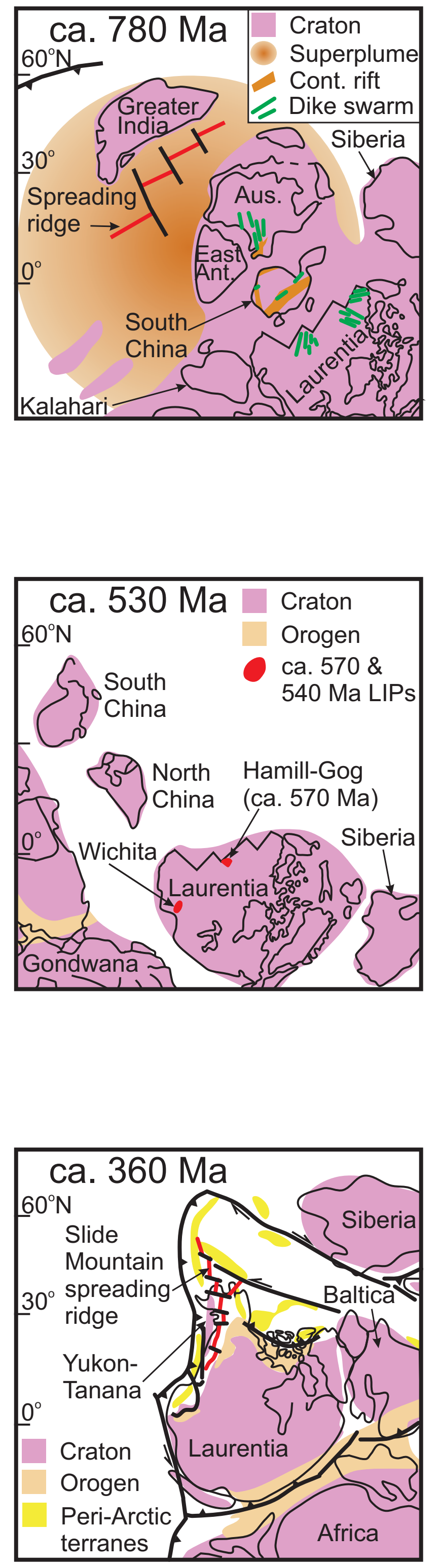
Shear wave velocity at the core-mantle boundary and equatorial cross-section (modified from Burke, 2011)


00°E
60°N
30°
30°
60°S
-2.5 -1.0 0.0 1.0 2.5
Gradient of shear wave velocity (dVs, %)
PGZ at ca. -1% dVs
SW Indian ridge
Sumatra
New Guinea
DMM
Lower mantle
660 km
Africa
PGZ
Outer core (liquid)
Inner core (solid)
FOZO + EM1 + HIMU
Mid-Atlantic ridge
South America
Sinking mantle
Upper mantle
East Pacific rise
Continental lithosphere
Oceanic lithosphere and arc material
Oceanic spreading centers
Ultralow-velocity zones
Low shear wave velocity provinces
Elevated geoid heights & 660-km changes
Depressed geoid heights & 660-km changes

Plume generation zones (PGZ) outline two large low shear wave velocity provinces (LLSVP) at the core-mantle boundary (D″), which were stable in the present position for at least hundreds of m.y. (Burke, 2011).

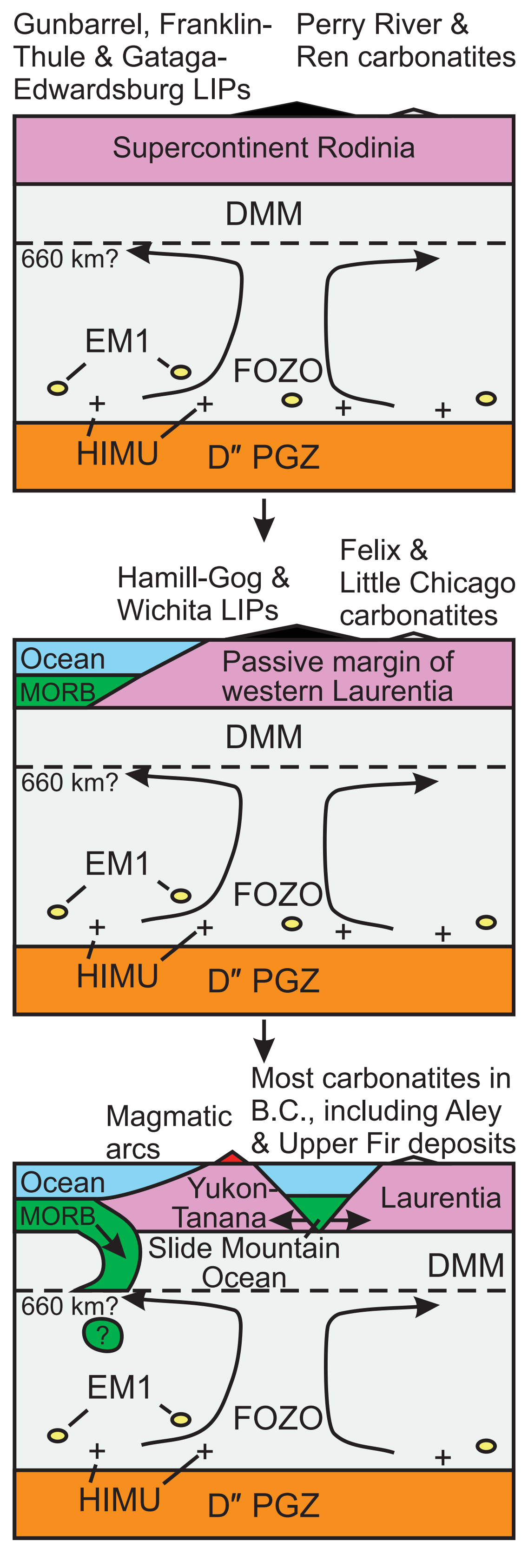
Paleogeography

Reconstructions of Neoproterozoic to Late Paleozoic continents (modified from Li et al., 2008; Ernst & Bleeker, 2010; Nelson et al., 2013)


ca. 780 Ma
60°N
30°
0°
Greater India
Spreading ridge
Aus.
East Ant.
South China
Kalahari
Laurentia
Siberia
Craton
Superplume
Cont. rift
Dike swarm
ca. 530 Ma
60°N
0°
South China
North China
Hamill-Gog (ca. 570 Ma)
Wichita
Laurentia
Siberia
Gondwana
Craton
Orogen
ca. 570 & 540 Ma LIPs
ca. 360 Ma
60°N
30°
0°
Slide Mountain spreading ridge
Yukon-Tanana
Siberia
Baltica
Laurentia
Africa
Craton
Orogen
Peri-Arctic terranes

Paleogeographic reconstructions place the western margin of Laurentia, and hence the 810-330 Ma British Columbia alkaline province, above the equatorial LLSVP marked by a long-lived plume-generation zone (PGZ) at the core-mantle boundary. Therefore, we suggest that parental magmas of carbonatites and related rocks of the British Columbia alkaline province episodically tapped a long-lived, deep-mantle plume from the PGZ during a period of ca. 480 Ma since the Neoproterozoic.

Summary model


Gunbarrel, Franklin-Thule & Gataga-Edwardsburg LIPs
Perry River & Ren carbonatites
Supercontinent Rodinia
DMM
660 km?
EM1
FOZO
HIMU
D″ PGZ
Hamill-Gog & Wichita LIPs
Felix & Little Chicago carbonatites
Ocean
MORB
Passive margin of western Laurentia
DMM
660 km?
EM1
FOZO
HIMU
D″ PGZ
Magmatic arcs
Most carbonatites in B.C., including Aley & Upper Fir deposits
Ocean
MORB
Yukon-Tanana
Laurentia
Slide Mountain Ocean
DMM
660 km?
?
EM1
FOZO
HIMU
D″ PGZ

ca. 810-700 Ma

Protracted breakup of the supercontinent Rodinia due to arrival of a deep-mantle plume (e.g., Li et al., 2008).

ca. 500 Ma

Passive margin development on the western flank of Laurentia (Bond & Kominz, 1984; Ross, 1991; Colpron et al., 2002).

ca. 360-330 Ma

Rifting the continental margin and initiating the Slide Mountain ocean as a back-arc basin (e.g., Nelson et al., 2013).

Conclusions

British Columbia carbonatites are indistinguishable from worldwide carbonatites generated by deep-mantle plumes. We suggest that the Cordilleran examples were derived from a long-lived, deep-level mantle plume that was tapped episodically since the Neoproterozoic.

Acknowledgments

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Selected references cited

Mitchell, R., Chudy, T., McFarlane, C.R.M., and Wu, F.-Y., 2017. Trace element and isotopic composition of apatite in carbonatites from the Blue River area (British Columbia, Canada) and mineralogy of associated silicate rocks. Lithos, 286-287, 75-91.

Rukhlov, A.S., Chudy, T.C., Arnold, H., and Miller, D., 2018. Field trip guidebook to the Upper Fir carbonatite-hosted Ta-Nb deposit, Blue River area, east-central British Columbia. British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Survey GeoFile 2018-6, 67 p.