



Early Paleozoic post-breakup magmatism along the Cordilleran margin of western North America: New zircon U-Pb age and whole-rock Nd- and Hf-isotope and lithogeochemical results from the Kechika group, Yukon, Canada

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ABSTRACT

Post-breakup magmatic rocks are recognized features of modern and ancient passive margin successions around the globe, but their timing and significance to non-plume-related rift evolution is generally uncertain. Along the Cordilleran margin of western North America, several competing rift models have been proposed to explain the origins of post-breakup igneous rocks that crop out from Yukon to Nevada. New zircon U-Pb age and whole-rock geochemical studies were conducted on the lower Paleozoic Kechika group, south-central Yukon, to test these rift models and constrain the timing, mantle source, and tectonic setting of post-breakup magmatism in the Canadian Cordillera. The Kechika group contains vent-proximal facies and sediment-sill complexes within the Cassiar platform, a linear paleogeographic high that developed outboard of continental shelf and trough basins. Chemical abrasion (CA-TIMS) U-Pb dates indicate that Kechika group mafic rocks were generated during the late Cambrian (488–483 Ma) and Early Ordovician (473 Ma). Whole-rock trace-element and Nd- and Hf-isotope results are consistent with the low-degree partial melting of an enriched lithospheric mantle source during margin-scale extension. Equivalent continental shelf and trough rocks along western North America are spatially associated with transfer-transform zones and faults that were episodically reactivated during Cordilleran rift evolution. Post-breakup rocks emplaced along the magma-poor North Atlantic margins, including those near the Orphan Knoll and Galicia Bank continental ribbons, are proposed modern analogues for the Kechika group. This scenario calls for the release of in-plane tensile stresses and off-axis, post-breakup magmatism along the nascent plate boundary prior to the onset of seafloor spreading.

INTRODUCTION

The western or Cordilleran margin of ancestral North America (Laurentia) is widely assumed to be the result of Tonian–Ediacaran rifting and Ediacaran–Cambrian fragmentation of supercontinent Rodinia (e.g., Stewart, 1972; Colpron

et al., 2002; Li et al., 2008; Macdonald et al., 2012). Despite several decades of research on Cordilleran margin development, there remain many open questions about the precise age and paleogeographic setting of Neoproterozoic to lower Paleozoic rift-related rock units that crop out in the western United States and western Canada. Of particular interest are poorly dated, Cambrian–Ordovician volcanic and intrusive rocks (Figs. 1A and 1B) that postdate the rift to drift transition and onset of passive margin sedimentation along western North America by up to 40 m.y. (e.g., Souther, 1991; Goodfellow et al., 1995; Cecile et al., 1997; Lund, 2008). The evidence for non-plume-related, post-breakup magmatism within modern and ancient passive margin successions around the globe is puzzling (e.g., Jagoutz et al., 2007; Bronner et al., 2011), and the presence of lower Paleozoic igneous rocks along western North America is not easily reconciled with published scenarios for Ediacaran–Cambrian lithospheric breakup and subsequent thermal subsidence (e.g., Bond et al., 1985). The purpose of this article is to reexamine the Tonian–early Paleozoic rift evolution of western North America and to test published models for Cordilleran margin development through new, targeted studies of post-breakup volcanic strata in Yukon, Canada.

The Gunbarrel magmatic event (780 Ma; e.g., Harlan et al., 2003; Sandeman et al., 2014) and deposition of the Windermere Supergroup (e.g., Stewart, 1972; Link et al., 1993) record the Tonian–Cryogenian stages of Cordilleran rift evolution. These early rift episodes thinned and weakened Cordilleran lithosphere (Yonkee et al., 2014) and were likely associated with strike-slip deformation in some regions of western Laurentia (Strauss et al., 2015). Magmatic activity continued through the Cryogenian (ca. 720–640 Ma) in southeastern Yukon (Pigage and Mortensen, 2004), northern British Columbia (Ferri et al., 1999; Eyster et al., 2018), and western United States (Lund et al., 2003, 2010; Fanning and Link, 2004; Keeley et al., 2013; Yonkee et al., 2014). Ediacaran (ca. 570 Ma) volcanic rocks and Ediacaran–lower Cambrian siliciclastic strata were deposited after a period of thermal subsidence and are considered the products of a second rift phase that resulted in lithospheric breakup (e.g., Devlin and Bond, 1988; Devlin, 1989; Lickorish and Simony, 1995; Warren, 1997; Colpron et al., 2002). Siliciclastic strata of this second rift phase unconformably overlie rocks of the Cryogenian rift episode throughout western North America (e.g., Stewart

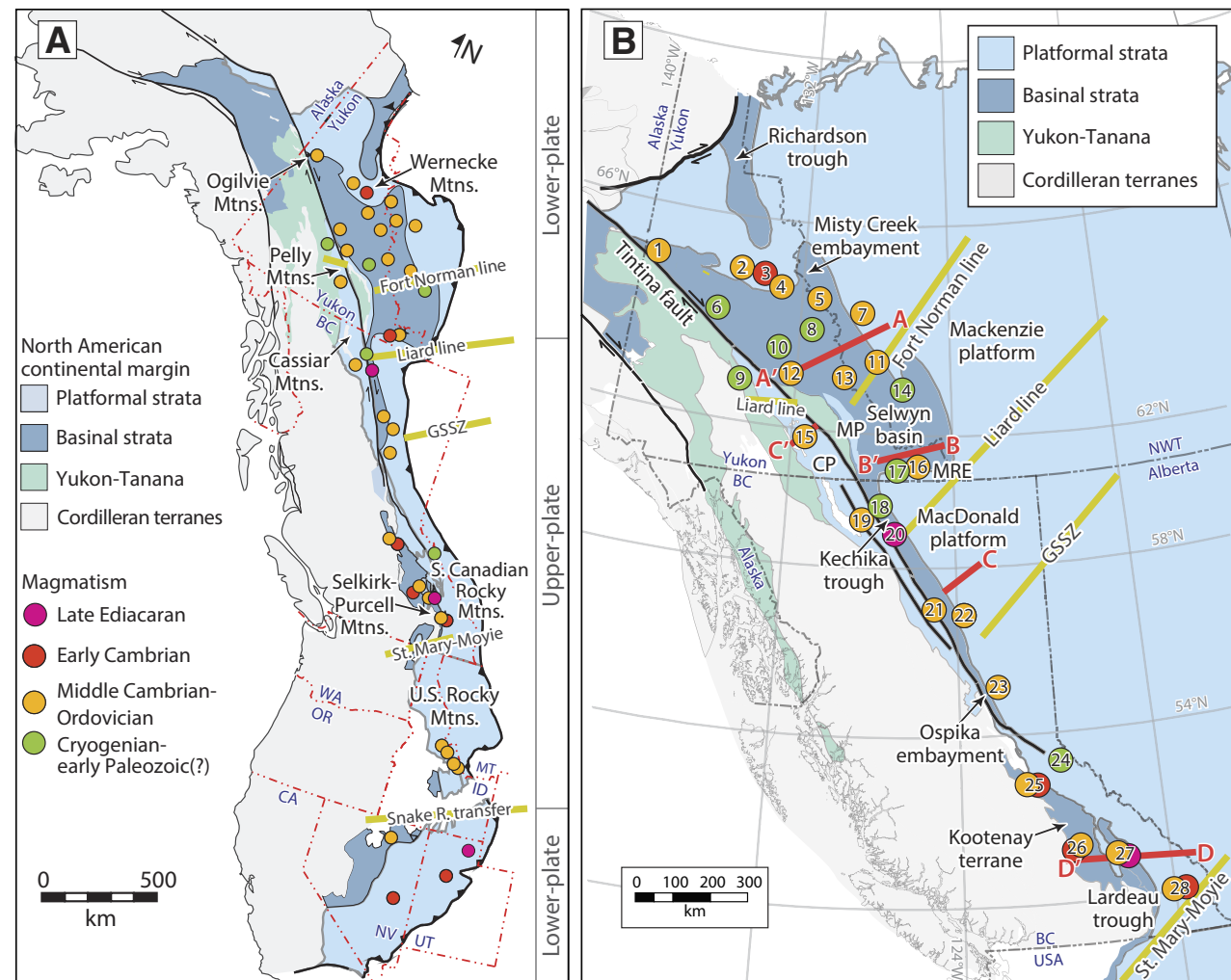


Figure 1. (A) Ediacaran to early Paleozoic magmatic rocks, tectonic elements, and crustal lineaments of the North American Cordillera adapted from Goodfellow et al. (1995), Lund (2008), and Colpron and Nelson (2009). Lower- and upper-plate divisions are from Lund (2008). (B) Map of the Canadian Cordillera highlighting the locations of Ediacaran to early Paleozoic magmatic rocks and key paleogeographic features. Numbers from 1 to 28 are references for Cordilleran margin magmatism provided in Table S1 (see text footnote 1). Abbreviations: CP—Cassiar platform; MP—McEvoy platform; MRE—Meilleur River embayment; Mtns.—Mountains; R.—River; GSSZ—Great Slave shear zone; BC—British Columbia; CA—California; ID—Idaho; MT—Montana; NV—Nevada; NWT—Northwest Territories; OR—Oregon; UT—Utah; WA—Washington.

and Suczek, 1977; Aitken, 1993; Prave, 1999; Lund, 2008; Yonkee et al., 2014) and are spatially associated with volcanic rocks in parts of southern British Columbia and northern Utah (Fig. 1A; Christie-Blick, 1997; Colpron et al., 2002; Ferri and Schiarizza, 2006).

An early Paleozoic age for lithospheric breakup is predicted from the thermal subsidence trends of upper Cambrian to Lower Ordovician platformal strata in the southern Canadian and U.S. Rocky Mountains (Armin and Mayer, 1983; Bond and Kominz, 1984; Bond et al., 1985; Levy and Christie-Blick, 1991). The inferred rift to post-rift transition is typically associated with a transition between coarse, locally feldspathic rocks and mature, shallow-water quartz sandstone (Bond et al., 1985; Devlin and Bond, 1988; Hein and McMechan, 1994). The transition lies near the Cambrian Stage 2 (late Terreneuvian) to Cambrian Stage 3 (early Series 2) boundary in southeastern British Columbia and within Cambrian Stage 2 in the western United States (time scale of Cohen et al., 2013; e.g., Bond et al., 1985; Magwood and Pemberton, 1988; Hein and McMechan, 1994). Post-rift, lower Cambrian carbonate strata with archaeocyathids overlie this syn-rift, siliciclastic succession (Read, 1980; Fritz et al., 1991; Paradis et al., 2006). In addition to the prominent Ediacaran–Cambrian unconformity (e.g., Devlin and Bond, 1988), upper Ediacaran quartz arenite units and lower Cambrian carbonate strata unconformably overlie Neoproterozoic to Mesoproterozoic rocks (e.g., Kubli and Simony, 1992; Colpron et al., 2002). Lower Cambrian successions also include poorly dated mafic volcanic rocks with ocean-island basalt (OIB)– to normal mid-ocean ridge basalt (N-MORB)–like geochemical signatures in Yukon (e.g., Abbott, 1997; Murphy, 1997; Milidragovic et al., 2006), southern British Columbia (e.g., Kubli and Simony, 1992; Ferri and Schiarizza, 2006; Logan and Colpron, 2006; Paradis et al., 2006), and western United States (e.g., Morris and Lovering, 1961; Kellogg, 1963; Yonkee et al., 2014).

Post-breakup volcanism is not a predicted outcome of pure- or simple-shear rift scenarios that have populated the Cordilleran literature since the early 1980s. For example, Bond and Kominz (1984) and Bond et al. (1984, 1985) used the pure-shear rift model of McKenzie (1978) to estimate subsidence patterns within stable Cordilleran shelf strata (Fig. 2A). Pure-shear scenarios predict uniform lithospheric extension that results in symmetric conjugate margins with syn-rift magmatism invoked to reduce lithospheric strength (e.g., Buck, 2004). The simple-shear rift models of Lister et al. (1986, 1991) were subsequently used to explain the asymmetry of the Cordilleran margin (Fig. 2B) and continued reactivation of lithospheric-scale lineaments during the Paleozoic (e.g., Christie-Blick and Levy, 1989; Hansen et al., 1993; Cecile et al., 1997; Tosdal et al., 2000; Lund, 2008). Simple-shear models predict that detachment faults separate the rifted margin into conjugate, upper- and lower-plate margin pairs with transfer-transform zones bounding different plate-margin segments (Fig. 2B). These zones of lithospheric weakness offset contrasting structural domains and provide focal points for mantle-derived magmatism (Thomas, 2006). Upper-plate regions undergo less crustal extension and result in narrow margins with syn-rift uplift being accommodated by magmatic underplating. The lower plate undergoes a greater degree of extension, which results in a wide area of lithospheric thinning and highly attenuated continental crust.

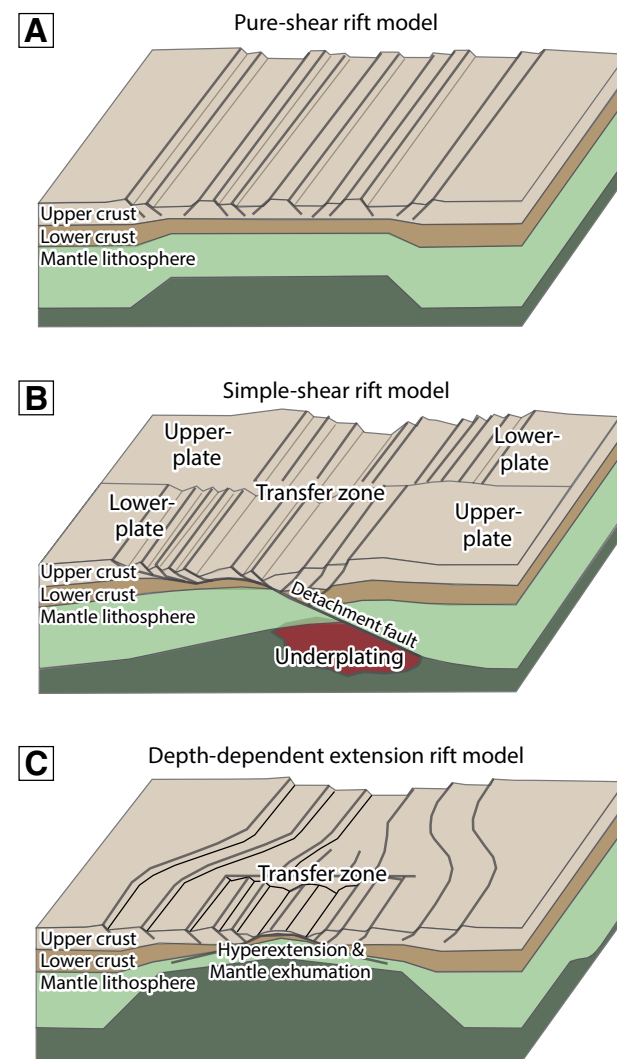


Figure 2. Simplified kinematic models for Cordilleran rift evolution adapted from Yonkee et al. (2014). (A) Pure-shear rift model with uniform lithospheric thinning based on McKenzie (1978). (B) Simple-shear rift model with heterogeneous thinning of upper and lower lithosphere based on Lister et al. (1986, 1991). Magmatism in the simple-shear model mostly occurs beneath upper-plate margins during the syn-rift to post-rift phase. (C) Depth-dependent rift model with lithospheric thinning and necking based on Davis and Kusznir (2004). Syn-breakup magmatism in this model is voluminous in outboard areas with a significant contribution from the depleted asthenospheric mantle (e.g., Eddy et al., 2017), whereas post-breakup magmatism occurs across the nascent plate boundary and is represented by low-volume alkaline volcanism derived from enriched mantle sources.

TABLE S1
Compilation of Ediacaran-early Paleozoic magmatic ages shown in Figure 1B.

Location 1
<i>Dempster Volcanics (Raboldite Fm.)</i>
Middle Cambrian-Ordovician
Abbott, G., 1997. Geology of the Upper Hart River Area, Eastern Oghive Mountains, Yukon Territory 116A/10, 116A/11. Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Bulletin 9, 92 p.
Green, I.H., 1972. Geology of Nash Creek, Larsen Creek, and Dawson map-area, Yukon Territory. Geological Survey of Canada, Memoir 364, doi:10.4095/100697.
Pigage, L.C., Roots, C.F., and Abbott, J.G., 2015. Regional bedrock geology for the Coal River map area (NTS-95D), southwest Yukon. Yukon Geological Survey, Bulletin 17, 155 p.
Roots, C.F. 1988. Cambro-Ordovician volcanic rocks in the eastern Dawson map area, Oghive mountains, Yukon, in Abbott, G., ed., Yukon Geology, Indian and Northern Affairs Canada, Geology Section, Whitehorse, Yukon, p. 81-87.
Strauss, J.V., Marmorek, P.J., Crowley, J.L., Colpron, M., King, J.D., Kammerer, W.T., and Taylor, J.F., 2016. Middle Cambrian extensional tectonism in Yukon, Canada: New age constraints and lithochemistry from the Dempster volcanics. <i>American Geophysical Union Fall Meeting Abstracts</i> , http://adsabs.harvard.edu/2016AGU/35M.1110D512S
Location 2
<i>Gull Lake Formation mafic volcanic suite</i>
Cambrian
Abbott, G., 1997. Geology of the Upper Hart River Area, Eastern Oghive Mountains, Yukon Territory 9116A/10, 116A/11. Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Bulletin 9, 92 p.
Nash volcanics
Middle Ordovician-Silurian

¹Supplemental Tables. Table S1: Compilation of Ediacaran-early Paleozoic magmatic rock units shown in Figure 1B. Table S2: Zircon CA-TIMS U-Pb isotope results and concordia plots. Table S3: Whole-rock major and trace element geochemical results. Table S4: Whole-rock Nd- and Hf-isotope geochemical results. Please visit <https://doi.org/10.1130/GES02044.S1> or access the full-text article on www.gsapubs.org to view the Supplemental Tables.

Whereas alkaline volcanism is inferred to characterize upper-plate margins (e.g., Lund, 2008), the role of volcanism along lower-plate margins is uncertain.

Yonkee et al. (2014) and Beranek (2017) proposed depth-dependent extension scenarios (Fig. 2C) with lithospheric thinning and necking that are broadly comparable to modern North Atlantic passive margin development. Such rift processes accommodate heterogeneous extension and decoupling of upper and lower lithosphere, which can result in hyperextension of continental crust and exhumation of continental mantle along magma-poor rift margins (Braun and Beaumont, 1989; Davis and Kuszner, 2004; Péron-Pinvidic et al., 2007; Brune et al., 2014). North Atlantic rift models suggest that lithospheric breakup is fundamentally linked to asthenosphere-derived magmatism across the nascent plate boundary with magmatic activity being most voluminous in outboard regions (Bronner et al., 2011). Off-axis, alkaline magmatism may subsequently occur across an embryonic plate boundary after breakup (Jagoutz et al., 2007), coincident with the deposition of breakup-related clastic successions that preserve the transition from breakup to thermal subsidence (Soares et al., 2012). North Atlantic rift scenarios may best explain the long-term stratigraphic evolution and timing of Neoproterozoic-early Paleozoic magmatism along the Cordilleran margin (Beranek, 2017); however, lower Paleozoic igneous rocks in western North America are poorly studied, and their relative age, petrogenesis, and proposed correlation with post-breakup units recognized offshore Newfoundland-Iberia remain speculative.

New high-precision analytical studies of lower Paleozoic igneous rocks are required to establish the timing and significance of post-breakup magmatism along the Cordilleran margin and test available rift models for western North America. In this article, we use a combination of chemical abrasion-thermal ionization mass spectrometry (CA-TIMS) zircon U-Pb geochronology and whole-rock trace-element and Nd- and Hf-isotope geochemistry to constrain the precise age and origin of the Kechika group, an aerially extensive volcanic-sedimentary succession (in south-central Yukon) that is representative of post-breakup magmatism in the Canadian Cordillera (Goodfellow et al., 1995; Tempelman-Kluit, 2012). The results allow us to test published rift scenarios for the Cordilleran margin and develop new working models for the Neoproterozoic-early Paleozoic evolution of western North America. We conclude that depth-dependent extension models best fit the available data for the Kechika group, with post-breakup rocks along the magma-poor Newfoundland-Iberia margins being suitable modern analogues for early Paleozoic magmatism.

■ LOWER PALEOZOIC STRATIGRAPHY OF THE NORTHERN CORDILLERA

Overview

The Cordilleran margin during Cambrian Series 2 to Ordovician time consisted of broad carbonate platforms that passed seaward into deep-water embayments and margin-parallel troughs (Fig. 3; e.g., Fritz et al., 1991; Cecile and

Norford, 1991; Nelson et al., 2013). Several paleogeographic highs, defined by areas with a history of non-deposition and/or thin shallow-water strata, periodically emerged during the early Paleozoic and include the long-lived Peace River arch of western Alberta (e.g., McMechan, 1990; Norford, 1990; Cecile and Norford, 1991; Cecile et al., 1997). The outer continental margin basins developed through periodic early Paleozoic crustal extension rather than purely thermal subsidence and locally have abundant volcanic deposits (Cecile and Norford, 1991; Cecile et al., 1997; Lund, 2008; see also stratigraphic compilation and volcanic rock occurrences in Table S1 in the Supplemental Tables¹). Coeval volcanism is also recognized within inner continental margin areas, although it is volumetrically restricted and represented by ultrapotassic and alkaline rocks and carbonatites (Pell, 1987, 1994; Mott, 1989; Norford and Cecile, 1994; Goodfellow et al., 1995; Leslie, 2009; Lund et al., 2010; Millonig et al., 2012).

Lithospheric-scale lineaments, including the northeast-trending Snake River transfer zone and the Liard line (Figs. 1A and 1B), border most of the significant Cambrian-Ordovician basins (Abbott et al., 1986; Turner et al., 1989; Cecile and Norford, 1991; Roots and Thompson, 1992; MacIntyre, 1998; Pyle and Barnes, 2003; Lund, 2008; Pigage, 2009; McMechan, 2012; Hayward, 2015). The spatial association of these transfer-transform faults with Proterozoic, Paleozoic, and Cenozoic igneous rocks implies that these structures represent long-lived, leaky zones that were continually reactivated (Goodfellow et al., 1995; MacIntyre, 1998; Lund, 2008; McMechan, 2012; Millonig et al., 2012; Audet et al., 2016; Cobbett, 2016). The Liard line is the most prominent lineament in the Canadian Cordillera and subdivides a wide, lower-plate margin from a narrow, upper-plate margin (Cecile et al., 1997).

Several margin-parallel basins were established within the upper-plate region of western Canada during the early Paleozoic. The Kechika graben of northern British Columbia was a precursor to the Kechika trough (Figs. 1B and 3) that developed during middle to late Cambrian extensional faulting and local uplift (e.g., Douglas et al., 1970; Fritz et al., 1991; Ferri et al., 1999; Post and Long, 2008; Pyle, 2012). Late Cambrian to Early Ordovician extension was associated with regional volcanism in the Ospika embayment and adjacent MacDonald platform (Figs. 1B and 3; MacIntyre, 1998; Ferri et al., 1999; Pyle and Barnes, 2000, 2003). The parautochthonous Kootenay terrane of southeastern British Columbia contains a Cambrian-Ordovician deep-water rift basin, the Lardeau trough (Fig. 1B), which developed adjacent to the St. Mary-Moyie transfer-transform zone and hosts at least three pulses of tholeiitic to alkalic magmatism (Fig. 3; Smith and Gehrels, 1992; Ferri and Schiarizza, 2006; Logan and Colpron, 2006; Paradis et al., 2006; Nelson et al., 2013). East of the Kootenay terrane, Cambrian-Ordovician (ca. 500 Ma) diatremes and alkaline lavas were emplaced in the White River trough (Godwin and Price, 1986; Pell, 1987; Parrish and Reichenbach, 1991; Kubli and Simony, 1992; Norford and Cecile, 1994; Millonig et al., 2012).

Syn- to post-breakup volcanic rocks are associated with the development of the Selwyn basin (Figs. 1B and 3) and related embayments in the lower-plate region of northwestern Canada (Cecile and Norford, 1991; Pyle and Barnes, 2003). Alkalic to ultrapotassic volcanic centers, sill complexes, dikes, and diatremes along the lower-plate margin were episodically emplaced during the

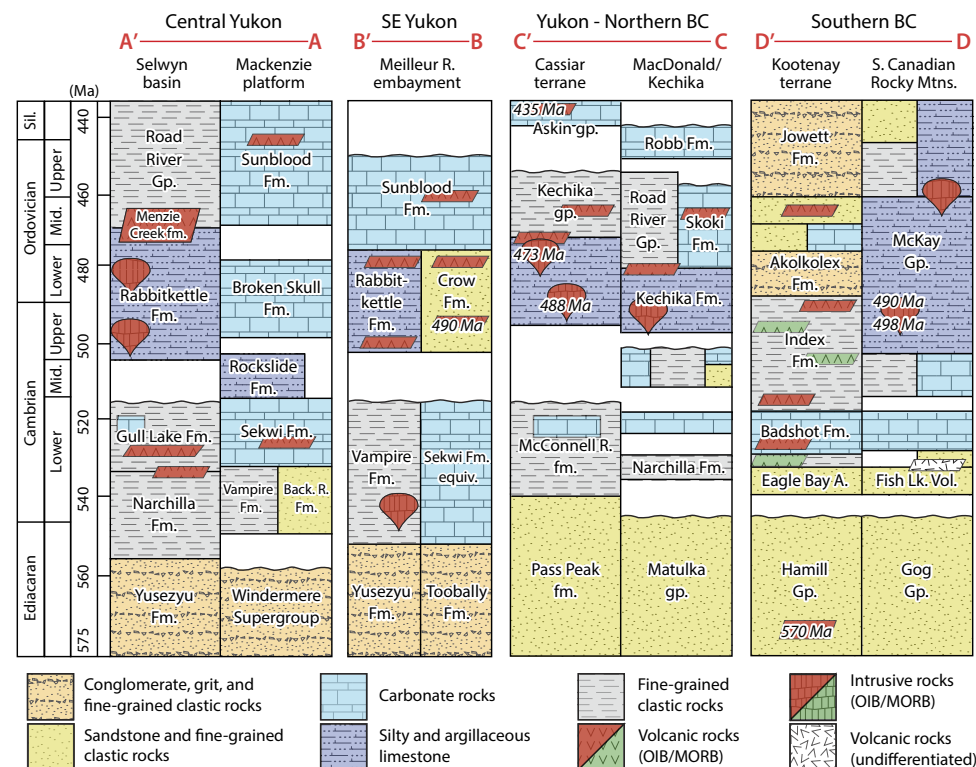


Figure 3. Simplified Ediacaran to lower Silurian stratigraphy of the Canadian Cordillera from central Yukon to southern British Columbia (see lines A–A', B–B', C–C', and D–D' in Fig. 1B). Italicized numbers are zircon U–Pb dates for igneous or tuffaceous rock units in the Hamill Group (569.6 ± 5.3 Ma; Colpron et al., 2002), Crow Formation (490.04 ± 0.13 Ma; Pigage et al., 2012), Kechika group (488.25 ± 0.44 Ma and 472.99 ± 0.70 Ma; this study), Askin group (ca. 435 Ma; this study), and southern Canadian Rocky Mountains (497.6 ± 2 Ma and 489.7 ± 8.4 Ma; Milonig et al., 2012). Stratigraphic compilations: Selwyn basin–Mackenzie platform (Gabrielse et al., 1973; Gordey and Anderson, 1993; Narbonne and Aitken, 1995; Pigage, 2004; Gordey, 2013; Oates et al., 2013; Pigage et al., 2015; Cobbett, 2016), Meilleur River embayment (Pigage et al., 2015), Cassiar terrane (Tempelman-Kluit, 2012), Kechika trough–MacDonald platform (Fritz et al., 1991; Ferri et al., 1999; Pyle and Barnes, 2003; Pyle, 2012), Kootenay terrane (Hein and McMechan, 1994; Colpron et al., 2002; Ferri and Schiarizza, 2006; Logan and Colpron, 2006; Paradis et al., 2006), southern Canadian Rocky Mountains (Bond and Kominz, 1984; Kubli and Simony, 1992; Hein and McMechan, 1994; Milonig et al., 2012; Nelson et al., 2013). Abbreviations: A. – assemblage; Back. R. – Backbone Ranges; Fm. – Formation (formal); fm. – formation (informal); Gp. – Group (formal); gp. – group (informal); Lk. – Lake; Mid. – Middle; MORB – mid-ocean ridge basalt; Mtns. – Mountains; OIB – ocean-island basalt; R. – River; S. – Southern; Sil. – Silurian; Vol. – Volcanics.

early Paleozoic (Hart, 1986; Roots, 1988; Abbott, 1997; Murphy, 1997; Cecile, 2000; Thorkelson et al., 2003; Pigage et al., 2015). Some volcanic rocks, such as the middle Cambrian Dempster volcanics in the Ogilvie Mountains of western Yukon (Roots, 1988; Abbott, 1997; Murphy, 1997; Cecile, 2000), are adjacent to Proterozoic growth faults (Thompson and Roots, 1982; Roots and Thompson, 1992). In areas such as the Misty Creek embayment (Fig. 1B), Middle Ordovician alkali basalts and foidites of the Marmot Formation are intercalated with basinal rocks that display a “steer’s head” rift profile (Cecile et al., 1982; Goodfellow et al., 1995; Leslie, 2009). The Meilleur River embayment (Liard depression) of southeastern Yukon contains >5.5 km of lower to mid-Paleozoic strata that were likely deposited during the reactivation of the adjacent Liard line (Cecile and Norford, 1991; Cecile et al., 1997). These strata overlie upper Cambrian to Middle Ordovician alkaline basalt and rhyolite of the Crow, Rabbitkettle, and Sunblood Formations that erupted during regional extension (Fig. 3; Gabrielse et al., 1973; Pigage, 2009; Pigage et al., 2012, 2015).

Middle Cambrian to Ordovician post-breakup magmatism in the western United States is best represented by Covada Group and Bradeen Hill assemblage mafic rocks in the Kootenay terrane of Washington State (e.g., Smith and

Gehrels, 1992), alkaline plutons of the Big Creek–Beaverhead belt in Idaho (Lund et al., 2010), a dike swarm in Colorado (Larson et al., 1985), and mafic alkaline rocks of the Roberts Mountain allochthon in Nevada (e.g., Watkins and Browne, 1989). Volcanic rocks in the southern Kootenay terrane and Roberts Mountain allochthon were probably deposited in an outer continental margin setting that underwent extensional or transtensional faulting (e.g., Turner et al., 1989). Late Cambrian detrital zircons with chondritic to subchondritic Hf-isotope compositions occur in the upper Cambrian St. Charles Formation of Idaho and likely indicate the uplift of the Lemhi arch and erosion of the Big Creek–Beaverhead belt during reactivation of Snake River transfer fault (Link et al., 2017).

Early Paleozoic crustal extension resulted in local hydrothermal activity and massive sulfide occurrences along the length of the Cordilleran margin (Goodfellow and Jonasson, 1986; Jennings and Jilson, 1986; Logan and Colpron, 2006). For example, mafic volcanic rocks and sills in the Anvil district of central Yukon (e.g., Menzie Creek formation, Fig. 3) overlie sedimentary exhalative base-metal deposits that were likely co-genetic with local normal faulting (Allen et al., 2000; Pigage, 2004; Cobbett, 2016). In southeastern British Columbia, the Cu–Zn Goldstream deposit is intercalated with post-breakup

volcanic rocks of the Index Formation (Fig. 3; Logan and Colpron, 2006). Similar base-metal occurrences are associated with Ordovician strata in the Roberts Mountain allochthon (e.g., Turner et al., 1989). Intrusive rocks and diatremes within the platform and adjacent craton are also linked with enrichments of rare-earth elements and other critical metals in southern British Columbia and micro-diamonds in northern Yukon (Godwin and Price, 1986; Pell, 1987; Norford and Cecile, 1994; Goodfellow et al., 1995; Leslie, 2009; Millonig et al., 2012).

Pelly Mountains, South-Central Yukon

The lower Paleozoic stratigraphy of the Pelly Mountains, south-central Yukon, consists of four depositional successions that include the Ketza, Kechika, Askin, and Harvey groups (Fig. 4; all units informal, Tempelman-Kluit, 2012). These units crop out within four major thrust sheets (Fig. 5) that developed during Jurassic–Cretaceous shortening and Cordilleran orogenesis (e.g., Evenchick et al., 2007). The Pelly Mountains region is mostly underlain by the Cassiar terrane, a parautochthonous block of the ancestral North American margin that underwent at least 430 km of post-Cretaceous dextral displacement along the Tintina fault (Gabrielse et al., 2006). Lower Paleozoic strata of the Cassiar terrane comprise part of a linear paleogeographic feature named the Cassiar platform (CP in Fig. 1B, Gabrielse, 1967; Fritz et al., 1991) or Pelly high (Cecile and Norford, 1991) that was located to the west of inboard elements such as the Selwyn basin, Kechika trough, and MacDonald platform. Allochthonous units of the pericratonic Yukon-Tanana and Slide Mountain terranes that evolved to the west of the North American margin occur in faulted contact with the Cassiar terrane along its western edge and as overlying klippen (Gordey, 1981). The western extent of the Liard line, which is offset by the Tintina fault, apparently transects the Pelly Mountains and places most of the Cassiar terrane in an upper-plate setting (Fig. 1B; Cecile et al., 1997; Hayward, 2015).

Ketza Group

Upper Neoproterozoic(?) to lower Cambrian rocks of the Ketza group represent the oldest exposed Cassiar terrane units in Yukon. The basal Pass Peak formation consists of quartzite and fine-grained siliciclastic rocks, whereas the overlying McConnell River formation contains calcareous to pyritic mudstone and carbonate lenses with archaeocyathid-bearing mounds (Fig. 4; Read, 1980; Tempelman-Kluit, 2012). The contact between the Ketza group and overlying Kechika group is poorly exposed and typically obscured by faulting (Campbell and Beranek, 2017). A middle Cambrian fossil gap in the Pelly Mountains region, however, suggests the presence of an unconformity (Tempelman-Kluit, 2012); a mid-Furongian unconformity is similarly inferred within the Cassiar terrane of northern British Columbia (Gabrielse, 1963, 1998; Taylor and Stott, 1973; Pyle and Barnes, 2001). The lower Cambrian Rosella Formation in the Cassiar Mountains, northern British Columbia, is equivalent

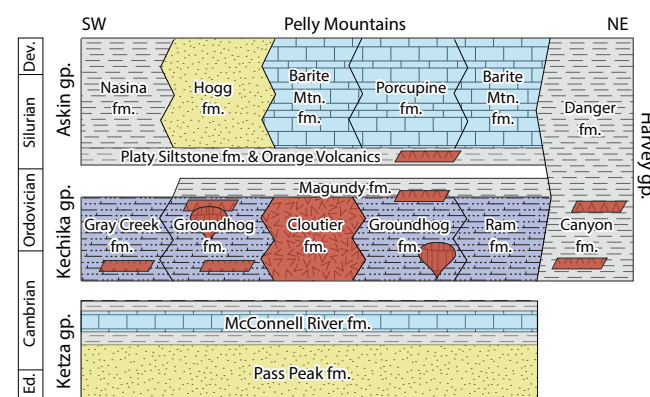


Figure 4. Lower Paleozoic stratigraphy of the Pelly Mountains compiled by Tempelman-Kluit (2012). Abbreviations: Dev.—Devonian, Ed.—Ediacaran, fm.—formation, gp.—group, Mtn.—mountain. Red polygons indicate mafic intrusions and lava flows.

to the McConnell River formation and locally intruded by m-thick mafic sills (Gabrielse, 1998).

Kechika Group

The Kechika group, the focus of the present study, is an upper Cambrian to Ordovician succession that includes the Cloutier, Groundhog, Ram, Gray Creek, and Magundy formations (Fig. 4; Tempelman-Kluit, 2012; Campbell and Beranek, 2017). Tempelman-Kluit (2012) defined the first four formations as being laterally equivalent and interfingering. The fifth stratigraphic unit, the Magundy formation, discontinuously caps the Groundhog, Cloutier, and Ram formations. Kechika group strata generally occur as narrow, northwest-trending, discontinuous belts across the Pelly Mountains (Fig. 5).

The Groundhog formation mostly consists of argillaceous to tuffaceous shale, silty limestone, and mafic tuff (Tempelman-Kluit, 2012). Basaltic to gabbroic sills occur throughout the unit, whereas subordinate volcanic and volcanoclastic rocks occur locally within the upper parts of the formation and overlying Magundy formation (Campbell and Beranek, 2017). The correlative Cloutier formation contains mafic volcanic and volcanoclastic rocks that vary in lateral extent (Tempelman-Kluit, 2012). Volcanic and volcanoclastic lithofacies within the Kechika group include pillow lava, sediment-matrix basalt breccia, and monomictic basalt breccia (Campbell and Beranek, 2017). These lithofacies are overlain by undated polymictic conglomerate and tuff at several localities (Campbell and Beranek, 2017).

The Magundy formation consists of black shale with minor quartz sandstone, basalt, and mafic tuff (Gordey, 1981; Tempelman-Kluit, 2012). Ordovician graptolites provide an upper age constraint for the Magundy formation (Gordey,

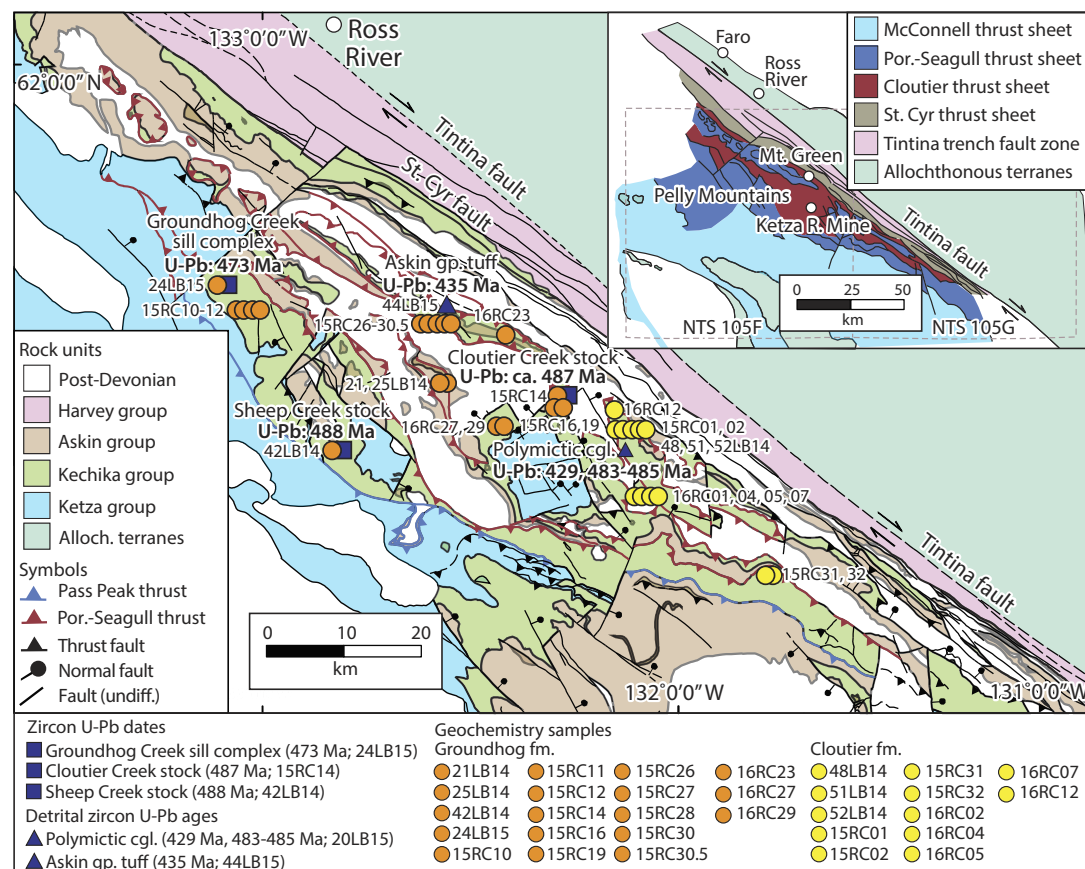


Figure 5. Simplified bedrock map of the Pelly Mountains region modified from Tempelman-Kluit (2012). Inset map shows the major tectonic elements and thrust sheets in the Quiet Lake (NTS 105F) and Finlayson Lake (NTS 105G) map areas. Blue squares and orange circles indicate Groundhog formation rock samples determined by zircon U-Pb geochronology and whole-rock geochemistry, respectively. Blue triangles indicate Askin group rock samples determined by zircon U-Pb geochronology. Yellow circles indicate Cloutier formation rock samples determined by whole-rock geochemistry. See text and Supplemental Tables S2–S4 [text footnote 1] for sample location information and data. Por. – Porcupine.

1981; Tempelman-Kluit, 2012). The upper Cambrian to Lower Ordovician Ram formation contains platy limestone and lesser shale that is comparable to the calcareous sections of the Groundhog formation. Greenstone, quartz mica schist, and siltstone of the Gray Creek formation may be metamorphosed equivalents of other Kechika group units (Tempelman-Kluit, 2012).

Basinal strata of the lower Kechika group are comparable to those of the Kechika Formation in the southern Cassiar terrane and Kechika trough and Rabbitkettle Formation in the Selwyn basin (Fig. 3; Cecile and Norford, 1991; Fritz et al., 1991; Gabrielse, 1998). Magundy formation black shale units are analogous to lower Road River group strata within the Selwyn basin and Kechika trough (Fig. 3; Pyle, 2012). Magmatic rocks that are equivalent to the Kechika group occur in the southern Cassiar Mountains (Gabrielse, 1963; Tempelman-Kluit, 2012), Glenlyon area of central Yukon (Gladwin et al., 2003; Black et al., 2003), and northern Rocky Mountains of British Columbia (Ferri et al., 1999).

Askin Group

The Askin group, along with the Sandpile Formation in the Cassiar Mountains, comprises part of the Silurian–Devonian Cassiar platform (Gabrielse, 1963, 1998; Cecile et al., 1997; Tempelman-Kluit, 2012). The McEvoy platform of eastern Yukon (EP in Fig. 1B) consists of similar shallow-water strata and likely represents a northern equivalent to the northeast of the Tintina fault (Gordey, 2013). Within the Pelly Mountains, the basal Askin group (Orange Volcanics member, Platy Siltstone formation of Tempelman-Kluit, 2012) contains mafic to intermediate lava flows, volcanic breccia, and tuff (Campbell and Beranek, 2017). Ordovician to Silurian shallow-water strata of the Sunblood and Haywire Formations are intercalated with similar volcanic rocks in the Meilleur River embayment area of southeastern Yukon (Fig. 3; Goodfellow et al., 1995; Pigage et al., 2015). The significance of the Silurian volcanism is beyond the

scope of this paper but may be related to early convergent margin tectonism along northwestern Laurentia (e.g., Pecha et al., 2016).

Harvey Group

The Harvey group is named for poorly understood, variably deformed and metamorphosed siliciclastic, carbonate, and volcanic rocks that crop out between the Tintina and St. Cyr faults (Fig. 5). Tempelman-Kluit (2012) proposed that the lower two units (Canyon and Danger formations) correlate with Kechika and Askin group strata, respectively (Fig. 4).

METHODS

CA-TIMS Zircon U-Pb Geochronology

Zircons from five rock samples that represent the broad regional extent of early Paleozoic magmatism in the Pelly Mountains were analyzed for CA-TIMS U-Pb geochronology (Table S2 [footnote 1]) at the Pacific Centre for Isotopic and Geochemical Research (Vancouver, British Columbia) following procedures outlined in Scoates and Friedman (2008). U-Pb dating studies of three gabbro units were conducted to determine the precise timing of Kechika group magmatism, whereas detrital zircons from two volcanoclastic rock samples were examined to constrain the depositional ages of upper Kechika group–lower Askin group strata (see Fig. 5 for sample locations). Zircon crystals were concentrated from rock samples using standard crushing, gravimetric, and magnetic separation methods, handpicked in alcohol under the binocular microscope, and annealed in quartz glass crucibles at 900 °C for 60 h. Annealed zircons were rinsed in ultrapure acetone and water, transferred into screw-top beakers, and chemically abraded in ultrapure HF and HNO₃ at ~175 °C for 12 h. The remaining zircon crystals were separated from the leachate, rinsed, weighed, and dissolved in HF and HNO₃ at ~240 °C for 40 h. Ion-exchange column techniques were used to separate and purify Pb and U. Isotopic ratios were measured with a modified single-collector VG-54R thermal ionization mass spectrometer equipped with analog Daly photomultipliers. U-Pb isotopic data were calibrated by replicate analyses of the NBS-982 reference material and values recommended by Thirlwall (2000). Data reduction was completed with the Microsoft Excel software of Schmitz and Schoene (2007). The Isoplot program of Ludwig (2003) was used to make Wetherill concordia diagrams and calculate weighted-mean averages and mean square of weighted deviate (MSWD) values.

Whole-Rock Lithochemistry

Thirty mafic volcanic and intrusive rocks from the Kechika group were analyzed for whole-rock major- and trace-element geochemistry (Table S3

[footnote 1]). Major-element oxide concentrations were acquired at Activation Laboratories (Ancaster, Ontario) by fused-bead X-ray fluorescence. Trace-element concentrations for six samples were acquired at the Pacific Centre for Isotopic and Geochemical Research by high-resolution inductively coupled plasma mass spectrometry (HR-ICPMS) (Element 2, Thermo Finnigan, Germany), whereas 24 samples were analyzed at Activation Laboratories using a research grade analytical package (4LITHO RESEARCH).

Eight of the samples were selected for whole-rock Nd- and Hf-isotope geochemistry (Table S4 [footnote 1]). Isotopic analyses were carried out at the Pacific Centre for Isotopic and Geochemical Research on a Nu Plasma II multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) (Nu Instruments Ltd., UK). Sample introduction followed the methods described in Weis et al. (2006, 2007) and occurred under dry plasma conditions using a membrane desolvator (DSN-100). For each analytical session, the standard solution JdNi (for Nd analyses) yielded average values of $^{143}\text{Nd}/^{144}\text{Nd} = 0.512088 \pm 0.000008$ ($n = 24$), and $^{143}\text{Nd}/^{144}\text{Nd} = 0.282157 \pm 0.000011$ ($n = 41$) for 2014 and 2015 samples, respectively. The JMC 475 standard solution (for Hf analyses) yielded average values of $^{176}\text{Hf}/^{177}\text{Hf} = 0.282156 \pm 0.000004$ ($n = 11$), and $^{176}\text{Hf}/^{177}\text{Hf} = 0.282157 \pm 0.000011$ ($n = 41$) for 2014 and 2015 samples, respectively. The results were corrected for instrumentation mass fractionation by exponentially normalizing to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ (O'Nions et al., 1979), and $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ (Patchett and Tatsumoto, 1981).

Sampling and Alteration

Rocks that preserve primary volcanic and intrusive textures were preferentially selected for geochemical analysis, whereas those containing veining, alteration, and textures associated with extensive fluid-rock interaction were avoided to limit post-crystallization geochemical modification. Fluid-rock interaction can lead to the mobility of elements that are otherwise thought to be immobile, such as P₂O₅ and Y, during the alteration of volcanic glass to clays (e.g., Price et al., 1991; Murton et al., 1992). Kechika group rock samples typically feature replacement of primary minerals with greenschist-facies assemblages (Tempelman-Kluit, 2012). Primary minerals in coarse-grained, mafic intrusive rocks include clinopyroxene, plagioclase, and Fe-Ti oxide minerals. Pyroxene is replaced by chlorite in most samples, whereas plagioclase is typically replaced by sericite. These observations are consistent with high loss on ignition (LOI; up to 14 wt%) values in some samples.

Immobile elements were used to classify Kechika group rocks because of the likelihood of major-element mobility (Spitz and Darling, 1978; MacLean and Barrett, 1993; Jenner, 1996; Piercey et al., 2002) as indicated by the lack of primary mineralogy in most samples. Elements that are usually immobile during hydrothermal alteration include Al, Ti, Th, Cr, HFSE, and REE (except La). Elements that are typically immobile include Sc, V, P, Co, and Ni (Pearce and Cann, 1973; Winchester and Floyd, 1977; Jenner, 1996; Pearce, 1996).

■ RESULTS

CA-TIMS Zircon U-Pb Geochronology

Sheep Creek Stock

The informally named Sheep Creek stock is an isolated, 1 km² body that intrudes Groundhog formation strata along the upper reaches of Sheep Creek, ~50 km southwest of Ross River. A sample of coarse-grained pyroxene gabbro (42LB14; Fig. 5) contains equant to elongate zircons that range in size from 100 to 125 µm. The crystallization age of the Sheep Creek stock is derived from three concordant zircons that yield a weighted-mean ²⁰⁶Pb/²³⁸U age of 488.25 ± 0.44 Ma (MSWD = 0.96; Figs. 6A and 6B). A fourth zircon gave a discordant result with a ²⁰⁶Pb/²³⁸U date of 486 Ma and likely reflects post-crystallization Pb loss.

Cloutier Creek Stock

The informally named Cloutier Creek stock is a ~1 km² body that intrudes Groundhog formation strata on the south side of Cloutier Creek, ~40 km south-east of Ross River. Coarse-grained pyroxene gabbro (15RC14; Fig. 5) from this location contains opaque, high-U zircons that dissolved completely during chemical abrasion leaching at standard conditions. Five zircons survived a relatively gentle leach and yielded strongly discordant data (20%–23%) that define a linear array interpreted to result from Pb loss, with an upper intercept of 486 ± 19 Ma and lower intercept of 167 ± 17 Ma (MSWD = 1.14; Fig. 6C). Five additional zircons that survived the first step underwent a second, higher temperature leach to assess whether less disturbed, possibly concordant sectors of grains exist. One of these dissolved completely, and only minor traces of material survived for the other four. The latter gave relatively imprecise results that lie along the same discordia array defined by gently leached grains. A discordia line constructed through results for all nine analyses yields intercepts of 487 ± 19 Ma and 167 ± 16 Ma (MSWD = 0.56; Fig. 6D). A crystallization age of ca. 487 Ma is estimated for the Cloutier Creek stock based on the available data.

Groundhog Creek Sill Complex

The informally named Groundhog Creek sill complex consists of well-exposed, 1- to >30-m-thick sills that intrude Groundhog formation strata along the north side of Groundhog Creek, ~40 km southwest of Ross River. The sills consist of fine- to coarse-grained mafic rocks that underlie an area of >12 km². A sample of medium-grained pyroxene gabbro (24LB15; Fig. 5) contains mostly equant zircons that range in size from 75 to 125 µm. Similar to the high-U zircons in the Cloutier Creek stock, only three of 20 grains from this pyroxene gabbro survived the chemical abrasion leaching procedure. The

crystallization age of the Groundhog Creek sill complex is therefore estimated by two concordant zircons that yield a weighted-mean ²⁰⁶Pb/²³⁸U age of 472.99 ± 0.70 Ma (MSWD = 0.85; Figs. 6E and 6F). An upper intercept age of ca. 1742 Ma is estimated for the core of a third, highly discordant zircon.

Polymictic Conglomerate

Cloutier formation strata to the east of the Ketz River Mine, ~50 km south-east of Ross River, mostly consist of vesicular to amygdaloidal massive basalt, pillow basalt, and associated volcanogenic rock units that were deposited in a submarine, vent-proximal environment (Campbell and Beranek, 2017). Variably deformed shale, limestone, and polymictic (limestone, mafic-intermediate volcanic rock) conglomerate units immediately overlie these Cloutier formation strata but have uncertain contact relationships with the underlying volcanic succession. Six detrital zircons analyzed from a sample of the polymictic conglomerate (20LB15; Fig. 5) yielded concordant ²⁰⁶Pb/²³⁸U ages of 428.92 ± 0.87 Ma, 483.43 ± 0.65 Ma, 484.34 ± 0.89 Ma, 485.01 ± 1.12 Ma, 1820.29 ± 4.23 Ma, and 2687.25 ± 7.73 Ma. Two zircons yielded discordant ages of ca. 432 Ma and 1745 Ma.

Askin Group Tuff

Kechika group strata within the upper reaches of Ram Creek, ~30 km south-southeast of Ross River, consist of a lower section of well-exposed, Groundhog formation shale, silty limestone, mafic intrusions, and volcanic to sedimentary lithic breccia, and an upper section of poorly exposed, Magundy formation black shale (Campbell and Beranek, 2017). Mafic to intermediate lava flows and tuff of the basal Askin group (Orange volcanics member of Tempelman-Kluit, 2012) overlie the Kechika group rocks. Four detrital zircons analyzed from a sample of orange-weathering Askin group tuff (44LB15; Fig. 5) yielded concordant ²⁰⁶Pb/²³⁸U ages of 435.37 ± 0.86 Ma, 1375.99 ± 3.37 Ma, 1840.66 ± 4.26 Ma, and 2023.17 ± 9.20 Ma. Two zircons yielded discordant ages of ca. 1658 Ma and 2677 Ma.

Lithogeochemistry

Element Mobility

Sodium, immobile element concentrations, and some incompatible-element ratios used to signify magmatic processes were plotted against the Al₂O₃/Na₂O alteration index of Spitz and Darling (1978) to semiquantitatively determine element mobility (Figs. 7A–7I). Most samples have low Al₂O₃/Na₂O ratios (23 of 30 samples yield Al₂O₃/Na₂O <10) with the exception of four Cloutier formation rocks, which have elevated Al₂O₃/Na₂O ratios (>25). Some elements

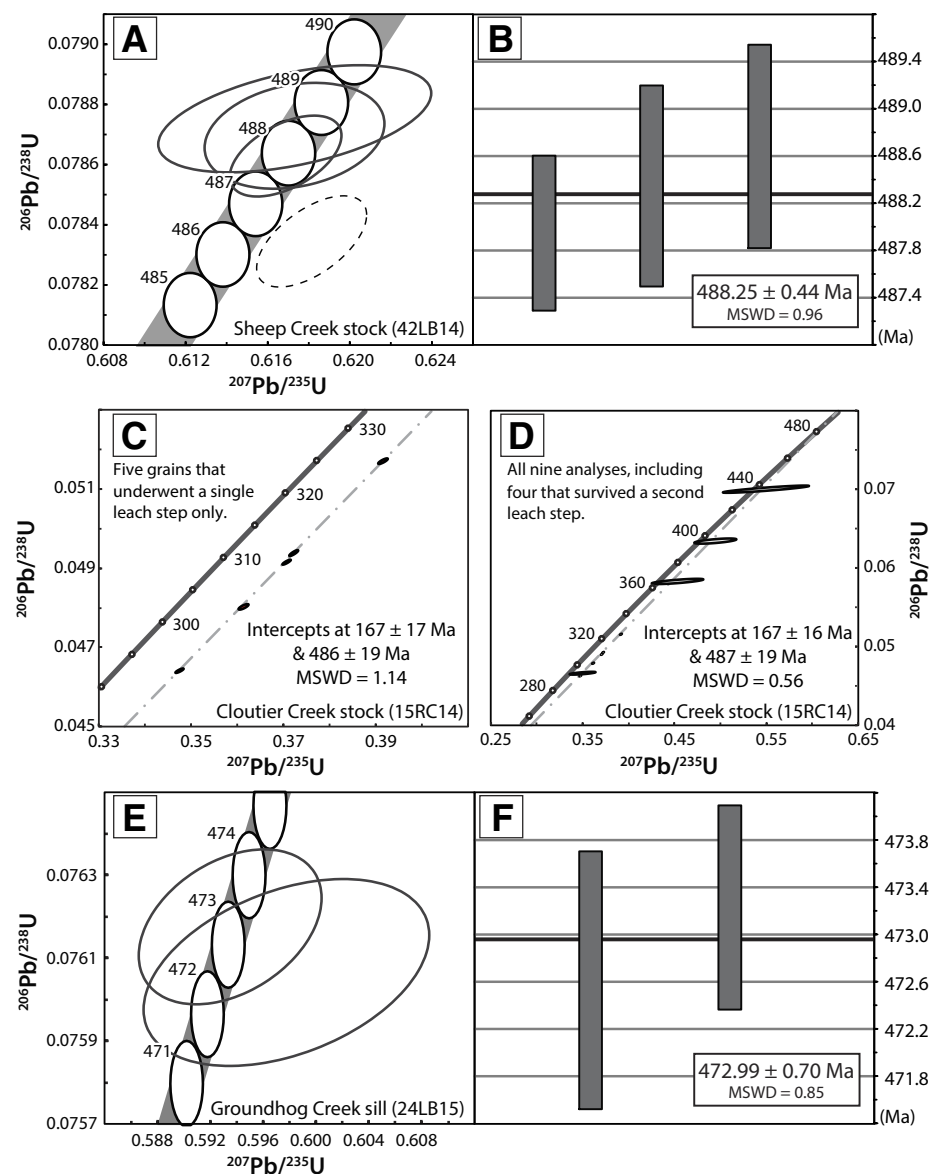


Figure 6. (A, C, D, E) Wetherill concordia plots of chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) U–Pb ages from samples 42LB14 (Sheep Creek stock), 15RC14 (Cloutier Creek stock), and 24LB15 (Groundhog Creek sill complex). Data are shown with 2σ error ellipses. Dashed ellipse is a data point not used for interpretation. (B, F) $^{206}\text{Pb}/^{238}\text{U}$ weighted-mean plots for samples 42LB14 and 24LB15. See text for age interpretations. MSWD—mean square of weighted deviates.

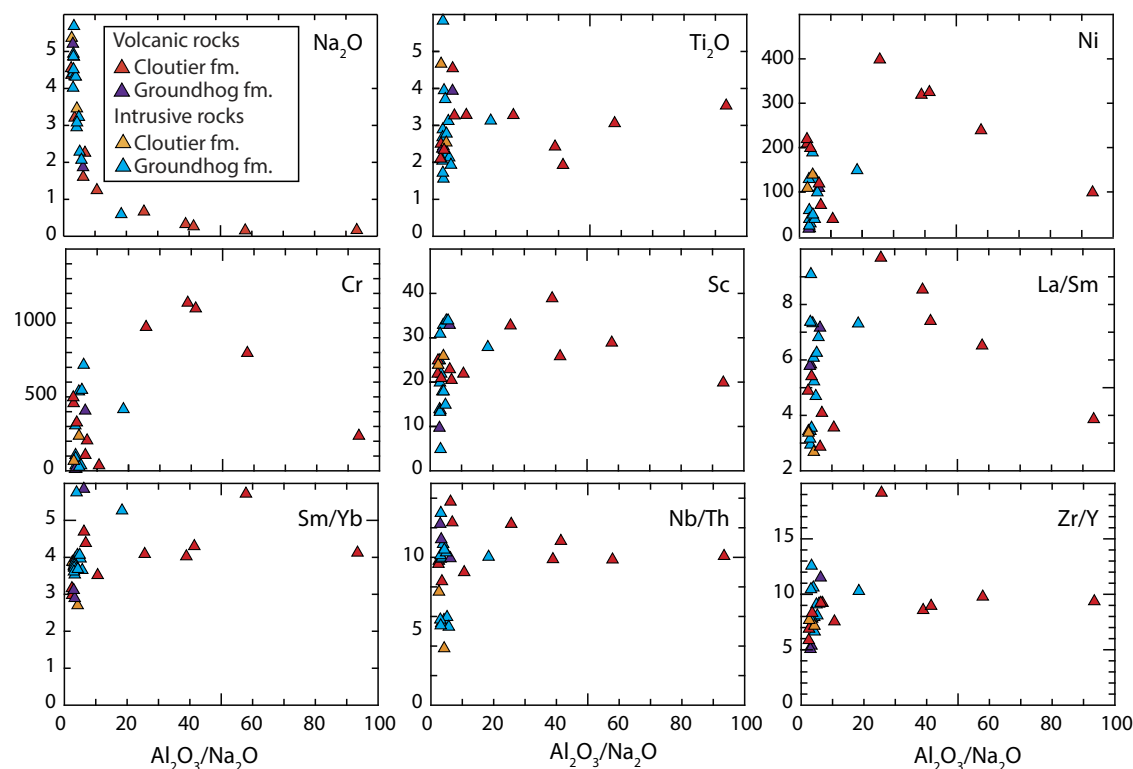


Figure 7. (A–I) Kechika group trace elements and element ratios plotted against the Spitz-Darling $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ alteration index (Spitz and Darling, 1978). Most elements and elemental ratios show a lack of correlation with the alteration index suggesting that elemental variation is independent of alteration. Five of the volcanic rock samples show a slight negative correlation for Ni, Cr, Sc, and Y, but this is not present in the remaining samples.

such as Ni, Cr, and Y can be variable, however; but most immobile element ratios show no relationship to alteration and suggest that the elements utilized (e.g., high-field-strength elements [HFSEs], REEs, and TiO_2) were immobile and suitable for delineating primary chemostratigraphy and igneous processes.

Cloutier and Groundhog Formation Volcanic Rocks

Volcanic rock samples from the Cloutier formation ($n = 11$) and Groundhog formation ($n = 3$) consist of pillow basalt and massive vesicular to amygdaloidal basalt. Kechika group volcanic rocks are basaltic ($\text{Zr}/\text{Ti} = 0.011\text{--}0.013$), moderately to extremely alkalic ($\text{Nb}/\text{Y} = 1.6\text{--}8.8$), and classified as alkali basalts to foidites (Fig. 8). The Zr/Ti ratio may signify crystal fractionation analogous to silica in a total alkali-silica diagram (Pearce, 1996). Zr behaves in a highly incompatible manner up to “acid-intermediate” composition magmas, whereas the compatibility of Ti increases during fractional crystallization of intermediate composition magmas (specifically due to crystallization of Fe-Ti

oxide minerals; e.g., Cann, 1970; Pearce, 1996; Piercey et al., 2002). Kechika group volcanic rocks display a broad range of transition metal contents such as Ni (18–400 ppm), Cr (15–1140 ppm), and Co (17–62 ppm) with moderate to low magnesium numbers (20–61; Fig. 9A). Aside from one basalt sample with high Ni and two with high Cr contents (400 ppm, 1102 ppm, and 1140 ppm, respectively), the majority of Kechika group volcanic rocks have transition metal contents and magnesium numbers that are below the expected values for primary melts (e.g., Ni = 400–500 and Cr > 1000 ppm; Mg # > 70). The variability of these elements is most likely linked to olivine and clinopyroxene (\pm chromite) fractionation for Ni and Cr, respectively. A decreasing Cr/Ni ratio with increasing Zr is consistent with field and petrographic identification of clinopyroxene phenocrysts in volcanic rocks and therefore clinopyroxene fractionation.

TiO_2 , Al_2O_3 , V, and Eu increase with increasing Zr content, although samples with elevated Zr contents (>300 ppm) have significant variability. The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio of the volcanic rocks (2.2–6.5; Fig. 9A) is relatively low, comparable to modern ocean-island basalts (OIB = ~5; Piercey et al., 2004) and

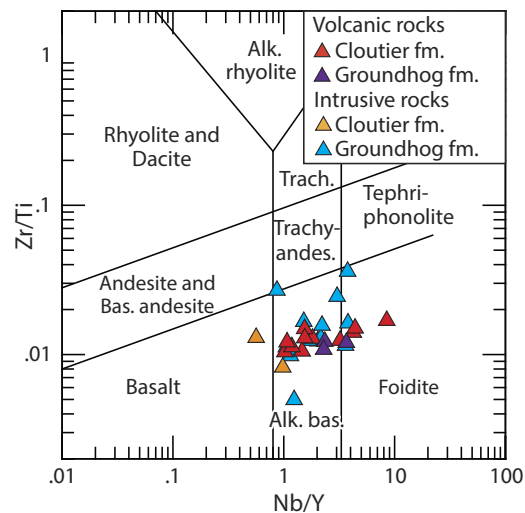


Figure 8. Nb/Y versus Zr/Ti plot of Winchester and Floyd (1977) as modified by Pearce (1996).

enriched mid-ocean ridge basalts (E-MORB = ~10; Sun and McDonough, 1989; Piercey et al., 2004).

The Nb/Y ratio indicates the degree of alkalinity (broadly analogous to Na in the total alkali-silica diagram) because the behavior of Nb is broadly comparable to Na during anhydrous mantle melting (e.g., Pearce, 1996). Nb and Y become fractionated due to Y becoming more compatible in mafic melts especially when in the presence of residual garnet (Pearce, 1996). The degree of alkalinity of basaltic magmas is controlled by factors including the enrichment of the mantle source area, degree of partial melting, and depth of melting (e.g., Pearce, 1996; Humphreys and Niu, 2009). The Ti/V ratio (46–85; Fig. 9D) is comparable to modern non-arc, transitional tholeiites to alkaline basaltic rocks (Shervais, 1982).

Cloutier and Groundhog formation volcanic rocks have steep, negative sloping, primitive mantle-normalized trace-element patterns (Figs. 10A and 10B) that are characterized by light rare-earth element (LREE) enrichment ($\text{La}/\text{Sm}_{\text{mn}} = 1.9\text{--}6.3$) relative to heavy rare-earth element (HREE) depletion ($\text{Sm}/\text{Yb}_{\text{mn}} = 3.3\text{--}6.5$) and a flat to positive Nb anomaly ($\text{Nb}/\text{Th}_{\text{mn}} = 1.0\text{--}1.6$). These geochemical signatures are comparable to global average OIB ($\text{La}/\text{Sm}_{\text{mn}} = 2.4$, $\text{Nb}/\text{Th}_{\text{mn}} = 1.4$, and $\text{Sm}/\text{Yb}_{\text{mn}} = 5.14$; Sun and McDonough, 1989) with more LREE-depleted samples approaching global E-MORB compositions ($\text{La}/\text{Sm}_{\text{mn}} = 1.6$, $\text{Nb}/\text{Th}_{\text{mn}} = 1.6$, and $\text{Sm}/\text{Yb}_{\text{mn}} = 1.2$; Sun and McDonough, 1989).

The immobile element ratios (Zr/Yb, Nb/Yb, and Nb/Th ratios; Figs. 11A and 11B) of some Groundhog and Cloutier formation volcanic rocks suggest derivation from a fertile, incompatible-element-enriched mantle source (e.g., Sun and McDonough, 1989; Pearce and Peate, 1995; Piercey and Colpron, 2009;

Piercey et al., 2012). The Nb/Ta (13–17) and Zr/Hf (36–48) ratios show evidence of fractionation relative to the chondritic uniform reservoir (CHUR; Nb/Ta = 17.6; Zr/Hf = 36.3; Sun and McDonough, 1989) and composition of global OIB and N-MORB (Zr/Hf for OIB = 35.9 and N-MORB = 36; and Nb/Ta for OIB = 17.8 and N-MORB = 17.7; Sun and McDonough, 1989).

Cloutier and Groundhog Formation Intrusive Rocks

Mafic intrusive rocks of the Groundhog formation ($n = 14$) and Cloutier formation ($n = 2$) consist of medium- to coarse-grained, >1-m-thick sills and stocks. Kechika group intrusive rocks have predominantly alkali basalt affinities (Fig. 8) but range from basaltic to foiditic ($\text{Nb}/\text{Y} = 0.56\text{--}3.8$). The intrusive rocks show greater degrees of fractionation than comagmatic lava flows as evidenced by the increased variability in the Zr/Ti ratio and a broad range of Ni (<20–190 ppm), Cr (<20–720 ppm), and Co (9–49 ppm) contents with moderate to low magnesium numbers (59–23; Fig. 9B). The transition metal contents and magnesium numbers are generally lower than those observed in the volcanic rocks and the expected value of primary mantle melts. Some of the more evolved gabbros (Zr >300 ppm) have Ni concentrations below the limit of detection (<20 ppm). The range of Cr contents, steep Cr versus Ni ratios in more evolved samples, and field and petrographic observations are consistent with clinopyroxene fractionation.

The elevated levels of magma evolution in some intrusive rocks (e.g., Zr contents >250 ppm) are associated with either a relative depletion or enrichment in Ti, Eu, V, and Al_2O_3 contents. Gabbro samples with enrichments in Ti, Eu, V, and Al_2O_3 relative to Zr are correlated with the presence of plagioclase and skeletal to interstitial Fe-Ti oxides in the gabbros. The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio (2.5–12; Fig. 9C) is greater than that of volcanic rocks but comparable to modern OIB to E-MORB.

Nb/Y values are consistent with Kechika group volcanic rocks and imply similar mantle source regions and mantle melting processes as modern alkali basalts (e.g., Pearce, 1996). Elevated Ti/V ratios in the intrusive rocks (46–154) range from the values associated with modern alkaline basalts (alkaline array) to transitional tholeiites (Fig. 9D; Shervais, 1982).

Kechika group intrusive rocks have steep, negative sloping, primitive-mantle normalized multi-element patterns with high to moderate LREE enrichment ($\text{La}/\text{Sm}_{\text{mn}} = 1.7\text{--}5.9$) and relatively steep HREE profiles ($\text{Sm}/\text{Yb}_{\text{mn}} = 3.0\text{--}6.4$) that are comparable to the Kechika group volcanic rocks and modern OIB to E-MORB (Figs. 10A and 10B). Some of the samples ($n = 8$) have a negative Nb/Th_{mn} ratio (0.46–1.6) and reduced LREE enrichment compared to other Kechika group rocks.

Zr/Yb, Nb/Yb, and Nb/Yb ratios reflect derivation from a fertile, incompatible-element-enriched mantle source (Figs. 11A and 11B). The Nb/La versus Nb/Th plot indicates the potential of crustal contamination in many of these rocks (Fig. 11A). Fractionation of the Nb/Ta and Zr/Hf ratio relative to CHUR is also present in the intrusive rocks of the Kechika group (e.g., Nb/Ta = 13–6.5; Zr/Hf = 39–48; Sun and McDonough, 1989; Green, 1995).

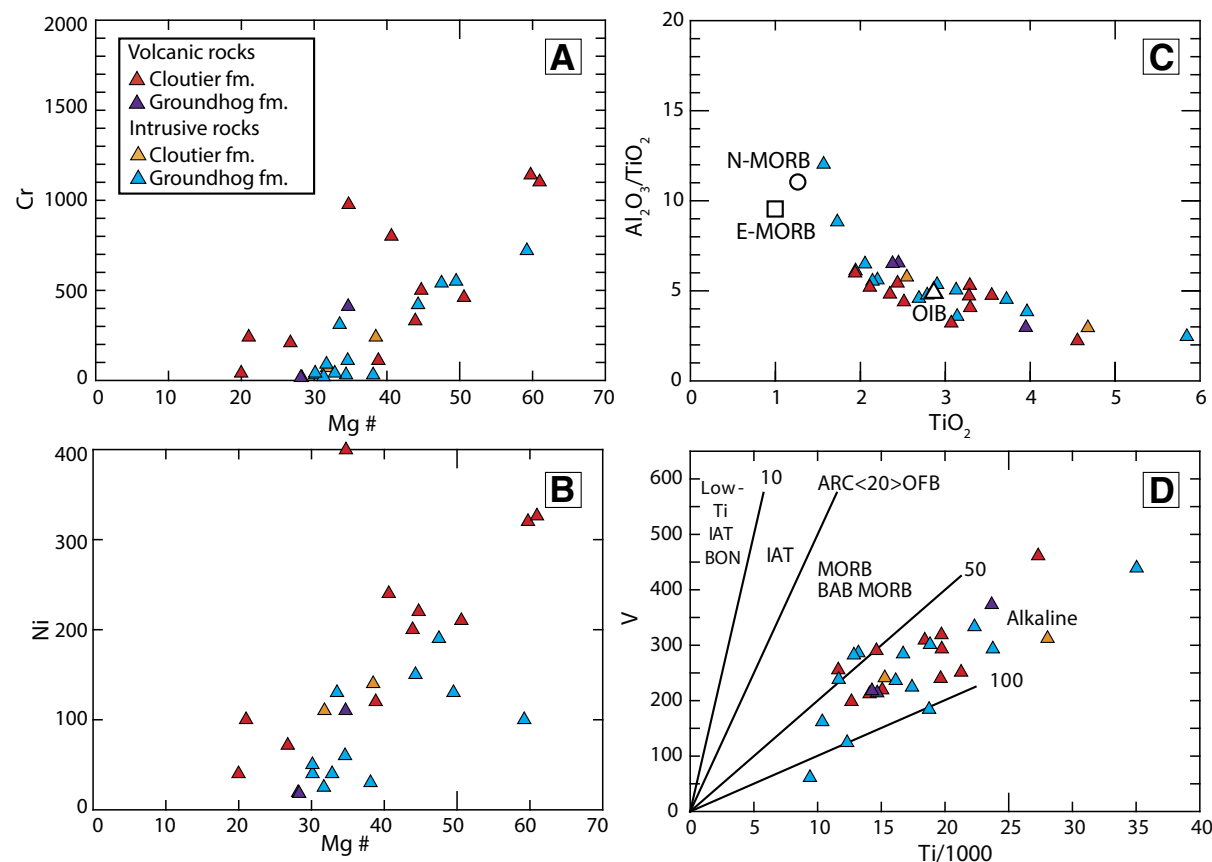


Figure 9. (A) Mg number versus Cr; (B) Mg number versus Ni; (C) Al_2O_3/TiO_2 versus TiO_2 plot after Piercey et al. (2012). Global average values for normal mid-ocean ridge basalt (N-MORB), enriched mid-ocean ridge basalt (E-MORB), and ocean-island basalt (OIB) from Sun and McDonough (1989). (D) The Ti-V discrimination diagram of Shervais (1982) indicating the alkaline to transitional tholeiite character of the Kechika group rocks. BAB—back-arc basalt; BON—boninite; IAT— island-arc basalt.

Nd- and Hf-Isotope Geochemistry

Initial epsilon values were calculated using the crystallization ages of 488 Ma and 473 Ma for the newly dated gabbros, and an intermediate age of 480 Ma was used for undated rocks and the Cloutier Creek stock. Kechika group volcanic rocks have ϵ_{Nd} values that range from +2.9 to +5.5 and ϵ_{Hf} values that range from +2.9 to +6.6 (Fig. 12A). These values are lower than expected for rocks sourced from the depleted mantle reservoir at 480 Ma, with ϵ_{Nd} values ranging between +7.8 and +9.3 based on the models of DePaolo (1981) and Goldstein et al. (1984), respectively, and ϵ_{Hf} values at +15.6 based on the model of Vervoort and Blichert-Toft (1999). This implies that the mantle source underwent relative

enrichment in LREE, resulting in a Sm/Nd ratio less than that of the depleted mantle reservoir (Goldstein et al., 1984; DePaolo, 1981). Kechika group intrusive rocks have ϵ_{Nd} values that range from -4.2 to +1.0 and ϵ_{Hf} values that range from -9.8 to +0.6. The negative values are comparable to an evolved crustal source (e.g., DePaolo, 1981), including shale units of the Kechika group that have ϵ_{Nd} values that range from -11.6 to -13.9 and ϵ_{Hf} values that range from -13.5 to -21.0 (Figs. 12A–12C; Tables S3 and S4 [footnote 1]). Depleted mantle model ages for the volcanic rocks range from T_{DM} (Nd) = 670 Ma to 1000 Ma and T_{DM} (Hf) = 840 to 1030 Ma. The model ages for the intrusive rocks range from T_{DM} (Nd) = 1220–1450 Ma and T_{DM} (Hf) = 1150–1620 Ma. Rocks with strongly negative ϵ_{Nd} and ϵ_{Hf} compositions also have low Nb/Th ratios (Figs. 13A and 13B).

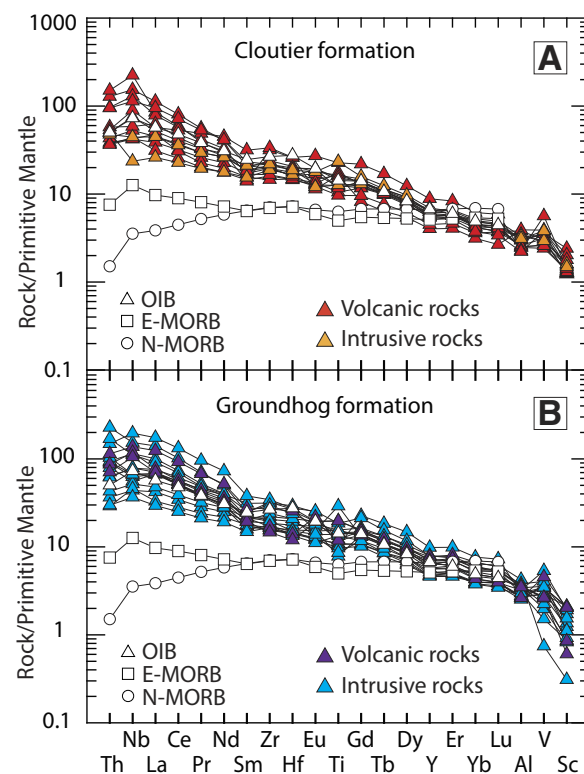


Figure 10. Primitive mantle-normalized multi-element plots with comparative modern analogues for (A) Kechika group volcanic rocks and (B) Kechika group intrusive rocks. Primitive mantle values and global normal mid-ocean ridge basalt (N-MORB), enriched mid-ocean ridge basalt (E-MORB), and ocean-island basalt (OIB) averages are from Sun and McDonough (1989) and McDonough and Sun (1995).

DISCUSSION

Timing and Emplacement History of the Kechika Group

The Sheep Creek and Cloutier Creek stocks, Groundhog Creek sill complex, and other Kechika group intrusive rocks likely originated as sill-sediment complexes (Campbell and Beranek, 2017) that were periodically emplaced into the outer Cordilleran margin during the latest Cambrian (ca. 488–487 Ma) and probably during the Early Ordovician (473 Ma). The sill-sediment complexes represent syn-sedimentary volcanism in sediment-rich basins that formed during the rifting of thinned continental crust and are spatially associated with transform-transfer zones such as the Liard line (e.g., Einsele, 1986; Naylor et al., 1999). The geochemistry and observed field relationships strongly suggest

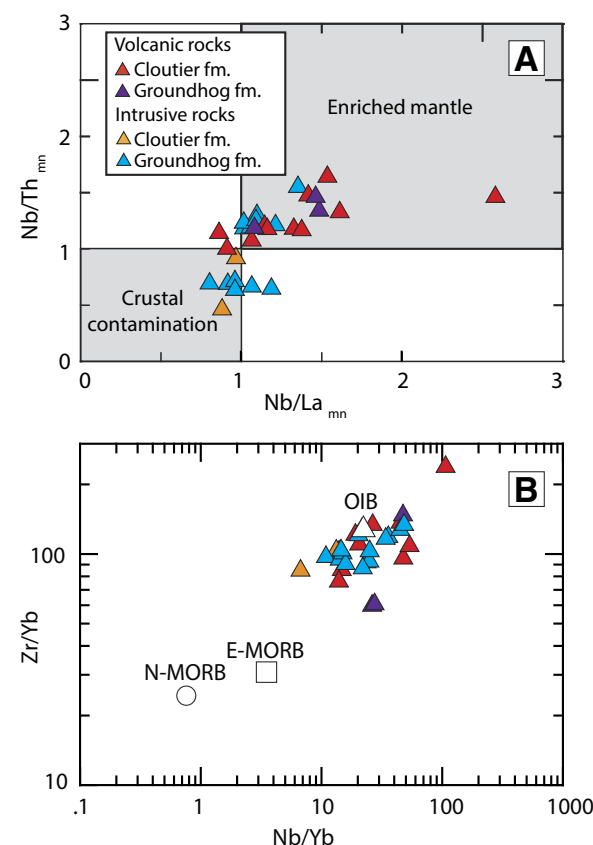


Figure 11. (A) Nb/Th_{mn} versus Nb/La_{mn} diagram adapted from Piercey et al. (2006) and based on the concept of Niu et al. (1999), where _{mn} = mantle normalized. Primitive mantle values are from Sun and McDonough (1989). (B) Zr/Yb versus Nb/Yb diagram of Pearce and Peate (1995). Kechika group rocks plot between enriched mid-ocean ridge basalt (E-MORB) and ocean-island basalt (OIB) end members and are therefore consistent with derivation from an incompatible-element-enriched mantle.

that these crystallization ages are also appropriate for the overlying and co-magmatic extrusive rocks, which originated at subaqueous volcanic centers. These U-Pb dates confirm the limited Cambrian to Ordovician fossil ages for the upper Kechika group (Tempelman-Kluit, 2012). Silurian detrital zircons within the polymictic conglomerate and Askin group tuff samples provide an upper age limit for Kechika group deposition. The presence of 485, 484, and 483 Ma detrital zircons in the polymictic conglomerate sample is consistent with local uplift and erosion of Kechika group rocks during the early Silurian (Tempelman-Kluit, 2012).

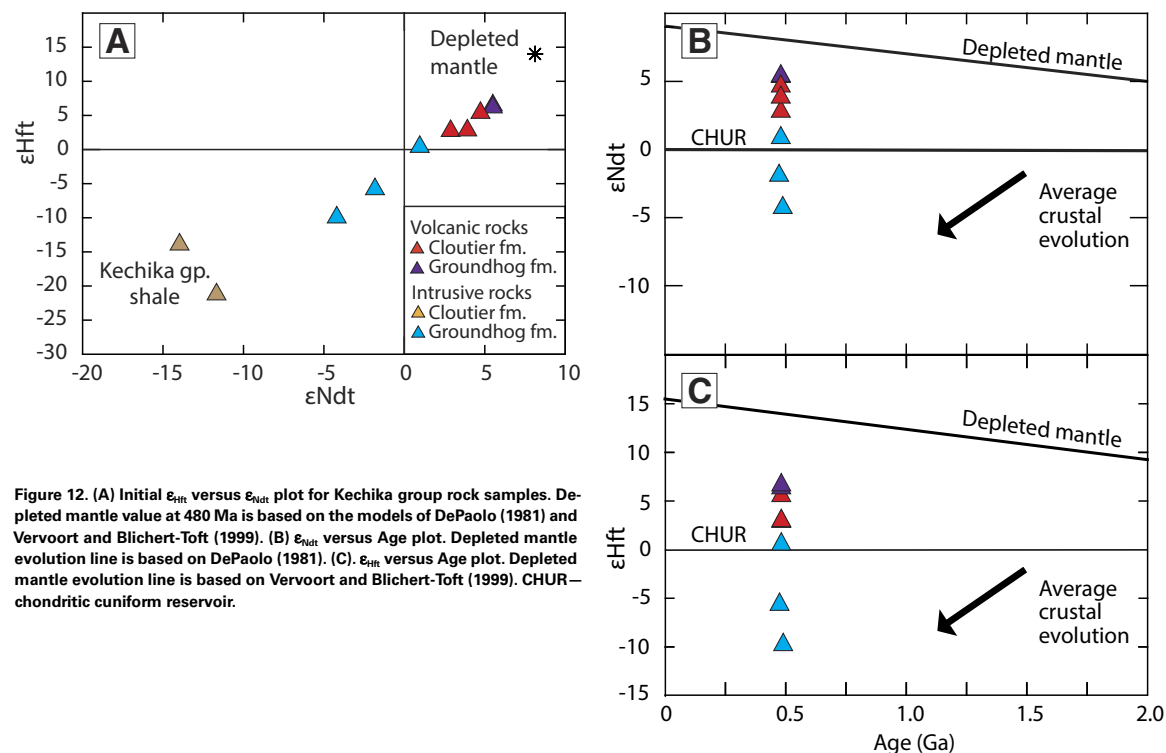


Figure 12. (A) Initial ϵ_{Hf} versus ϵ_{Nd} plot for Kechika group rock samples. Depleted mantle value at 480 Ma is based on the models of DePaolo (1981) and Vervoort and Blichert-Toft (1999). (B) ϵ_{Nd} versus Age plot. Depleted mantle evolution line is based on DePaolo (1981). (C) ϵ_{Hf} versus Age plot. Depleted mantle evolution line is based on Vervoort and Blichert-Toft (1999). CHUR—chondritic uniform reservoir.

Petrogenesis and Magma Source Components

The non-arc primitive mantle-normalized signatures of Kechika group rocks (Fig. 10) indicate that melt generation was likely associated with decompression melting associated with upwelling mantle. The OIB- to E-MORB-like primitive mantle-normalized signatures and alkaline geochemistry of Kechika group rocks indicate the derivation from a source enriched in incompatible elements (e.g., Pearce, 1996). This enrichment is a function of both the mantle source, as indicated by Nd- and Hf-isotope compositions, and melting processes, as indicated by trace-element data (e.g., Fitton, 1987; Pearce, 1996; MacDonald et al., 2001; Niu et al., 2011, 2012). Similar incompatible-element-enriched basalts are found in extensional settings, including continental rifts (e.g., Furman, 2007), attenuated continental margins (e.g., Pe-Piper et al., 2013), exhumed continental mantle lithosphere (e.g., Merle et al., 2009; Miranda et al., 2009), and areas with thickened oceanic lithosphere (e.g., Sun and McDonough, 1989; Niu et al., 2011). An increase in lithospheric thickness can inhibit asthenospheric mantle upwelling and therefore increase the overall depth of the melting interval. This increase in depth will increase the pressure of melting and reduce the volume

of melt (the lid effect; e.g., McKenzie and Bickle, 1988; Niu and O'Hara, 2007; Humphreys and Niu, 2009). Kechika group rocks show fractionation of Nb/Ta and Zr/Hf ratios relative to CHUR, similar to low-degree partial melting mantle processes for modern alkali basalts (e.g., ~1%–3%; Green, 1995; David et al., 2000). Kechika group rocks show fractionation of Nb/Ta and Zr/Hf ratios relative to CHUR, similar to low-degree partial melting mantle processes for modern alkali basalts (e.g., ~1%–3%; Green, 1995; David et al., 2000). A reduction in melt volume will therefore concentrate incompatible elements and volatiles, such as Na, Nb, HFSE, Ti, P, H₂O, and CO₂, present in the mantle source region (e.g., Edgar 1987; Pearce, 1996; Kogiso et al., 2003; Niu et al., 2011). Melting at sufficient depth produces the characteristic OIB signature with LREE enrichment relative to HREE. This signature likely reflects the melting of clinopyroxene in the presence of residual garnet (e.g., Ionov et al., 1993; Hirschmann et al., 2003; Sobolev et al., 2005) and implies that some amount of melting occurred below the garnet-spinel transition zone.

Kechika group volcanic rocks yield ϵ_{Nd} and ϵ_{Hf} values that are lower than those of the depleted mantle array at ca. 480 Ma but greater than CHUR. Published Nd-isotope data sets from OIB- and E-MORB-like mafic rocks along

the Cordilleran margin similarly indicate mantle sources with a long history of incompatible-element enrichment (e.g., Piercey et al., 2006; Piercey and Colpron, 2009). Kechika group intrusive rocks, however, yield chondritic to subchondritic ϵ_{Nd} and ϵ_{Hf} values that imply the involvement of a crustal source. In addition to the low Nb/Th_{mn} ratios, relative Ti depletions, and relatively high Zr/Ti ratios, these gabbroic rocks have broadly similar incompatible-element enrichment as the volcanic rocks. Although the volcanic rocks could be slightly older than the intrusive rocks, there are no observed field relationships that support a significant difference in age. The available stratigraphic data (e.g., Tempelman-Kluit, 2012) also agree with the U-Pb dates of the gabbroic rocks, and the trace-element geochemical similarities generally support a coeval relationship between the volcanic and intrusive rocks. A plot of ϵ_{Nd} and ϵ_{Hf} composition versus Nb/Th ratio (Figs. 13A and 13B) forms a mixing line between volcanic, intrusive, and coeval sedimentary rocks and is therefore consistent with influence from crustal material (e.g., crustal assimilation) either in the magma chamber or upon emplacement at higher crustal levels (e.g., Pearce, 1996; Piercey et al., 2006; Meade et al., 2009).

There are several mantle sources that could explain the Nd- and Hf-isotope compositions and incompatible-element enrichment of Kechika group volcanic rocks, including a mantle plume (e.g., Morgan, 1971), enriched “blobs” within the asthenospheric mantle (Fitton, 2007), and metasomatized mantle in the subcontinental lithosphere (Lloyd and Bailey, 1975; Halliday et al., 1995; Pearce, 1996) and/or within the lithosphere-asthenosphere boundary (e.g., Green et al., 2010; Niu et al., 2011; Schmerr, 2012). A plume origin for early Paleozoic volcanism along the Cordilleran margin has been discounted previously (Goodfellow et al., 1995) due to the margin-length scale of magmatism, duration and minor volume of magmatism, and proximity of volcanic rocks to major lineaments or faults. Goodfellow et al. (1995) concluded that potassic-ultrapotassic rocks in the northwestern Selwyn basin were sourced from the lithospheric mantle, whereas alkali basalts in the central Selwyn basin partially sampled an OIB-like asthenospheric domain (e.g., Fitton et al., 1988). The repeated melting of a metasomatized subcontinental lithospheric mantle source is consistent with the highly incompatible-element-enriched composition of early to mid-Paleozoic lavas (including ultrapotassic melts) along the inner Cordilleran margin (e.g., Foley, 1992; Goodfellow et al., 1995; Leslie, 2009; Millonig et al., 2012) and is presumably a significant contributor to the incompatible-element-enriched nature of mafic alkalic volcanic rocks in more outboard regions (e.g., Piercey et al., 2006; Piercey and Colpron, 2009). Metasomatism of Cordilleran lithospheric mantle could be linked with prolonged rifting and magmatic episodes that affected western North America during the Mesoproterozoic to Neoproterozoic (Piercey et al., 2006). For example, the Tonian (780 Ma) Muncho Lake dikes form part of the Gunbarrel magmatic event in British Columbia and are spatially associated with the Liard line (LeCheminant and Heaman, 1994; Ross et al., 2001; Harlan et al., 2003).

Metasomatism at the lithosphere-asthenosphere boundary by melt and/or volatiles may explain the incompatible-element enrichment of off-axis alkaline rocks and geophysical signature of the low-velocity zone (Green et al., 2010; Niu et al., 2011; Schmerr, 2012; Keller et al., 2017). This melt- and/or volatile-rich region

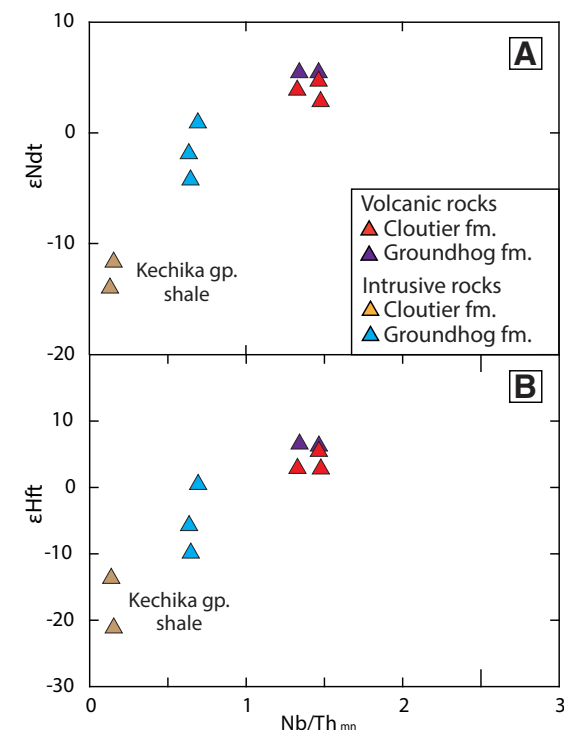


Figure 13. (A) Initial ϵ_{Nd} versus Nb/Th_{mn} and (B) Initial ϵ_{Hf} versus Nb/Th_{mn} plots where _{mn} = mantle normalized. These results suggest that the geochemical signatures of the intrusive rocks can be modeled as a mixture between Kechika group siliciclastic rocks and coeval volcanic rocks.

occurs at depths of <90 km along the eastern North American margin (Rychert et al., 2005), which is at or below the spinel-garnet transition in peridotite (~85 km; Wood et al., 2013). Melting of metasomatized mantle at the lithosphere-asthenosphere boundary beneath the eastern North American margin would therefore be consistent with the formation of the OIB-like signature in Cretaceous alkalic volcanic rocks within the Orpheus Graben, offshore Nova Scotia (e.g., Jansa and Pe-Piper, 1985). Mantle metasomatism at the base of the subcontinental lithospheric mantle may be analogous to that at the lithosphere-asthenosphere boundary of a growing oceanic lithosphere (Niu et al., 2012).

Data from the present study are consistent with the OIB-like signature of the Kechika group rocks originating through low-degree partial melting of an enriched metasomatized mantle source at the base of the highly attenuated continental lithosphere. The development of this metasomatized zone at the base of the continental margin lithosphere likely occurred following Neoproterozoic rifting and would provide an enriched (lithospheric?) mantle source for early to mid-Paleozoic lavas of the Cordilleran margin (e.g., Piercey et al., 2006).

Syn- to Post-Breakup Volcanism along the Cordilleran Margin

The high-precision zircon U-Pb ages reported from the Pelly Mountains provide evidence for continued volcanic activity at least 40 m.y. after lithospheric breakup along western North America. From a stratigraphic perspective, post-breakup rocks in the Pelly Mountains are analogous to more poorly constrained Cambrian–Ordovician volcano-sedimentary successions in British Columbia, Yukon, Washington, Idaho, and Nevada. For example, sediment-sill complexes similarly underlie the Menzie Creek and Crow formations in central and southeastern Yukon, respectively (Pigage, 2004; Pigage et al., 2015; Cobbett, 2016). The principal lithofacies of these volcanic successions are akin to those of Kechika group and consist of pillow basalt, basalt breccia, lapilli tuff, and epiclastic sandstone (Pigage, 2004, 2009). At the margin scale, there is evidence for middle Cambrian to Ordovician normal faults to be related to mafic volcanism throughout the Selwyn basin, Meilleur River embayment, Misty Creek embayment, Kechika trough, and Roberts Mountain allochthon (Cecile et al., 1982; Turner et al., 1989; MacIntyre, 1998; Pigage, 2004; Pigage et al., 2015). From central Yukon to northern British Columbia, Cambrian–Ordovician volcanism was coincident with shale deposition in relatively anoxic conditions (Fig. 3; Cecile et al., 1982; Abbott et al., 1986; Cecile and Norford, 1991; MacIntyre, 1998; Pyle and Barnes, 2000; Pigage, 2009; Gordey, 2013), suggesting that at least some sedimentation occurred in deep-marine environments (e.g., Goodfellow et al., 1995; MacIntyre, 1998). Farther south in the Roberts Mountain allochthon of Nevada, Middle to Late Ordovician greenstone and faulting are associated with a chert-argillite basinal sequence (Madrid, 1987; Turner et al., 1989).

Field evidence for Cambrian–Ordovician faults in the Pelly Mountains is lacking (Tempelman-Kluit, 2012), but the lithofacies, stratigraphic trends, and geochemical signatures of the Kechika group are similar to other extension-related depocenters in the Selwyn basin, Meilleur River embayment, and Misty Creek embayment. The similarities between these coeval volcanic centers suggest that analogous post-breakup, rift-related processes occurred throughout the early Paleozoic development of the Cordilleran margin. In the Gataga district of northern British Columbia, MacIntyre (1998) inferred that major facies boundaries between lower Paleozoic rock units formed through the reactivation of listric normal faults that originally bounded tilted fault blocks. It is therefore plausible that the basal units of the Kechika group (Cloutier, Groundhog, and Gray Creek formations), now separated by Mesozoic thrust faults, may have originally been deposited in a related setting.

Implications for Cordilleran Rift Models

The Cordilleran margin has a protracted rift evolution that includes >300 m.y. of crustal stretching and thinning, lithospheric breakup, and pre-, syn-, and post-breakup magmatism (e.g., Stewart, 1972; Colpron et al., 2002; Yonkee et al., 2014; Strauss et al., 2015). Although post-breakup, early Paleozoic magmatism has long been recognized in western North America (e.g., Goodfellow

et al., 1995; Lund, 2008), there are many open questions about the tectonic significance of Cambrian–Ordovician volcanic strata assigned to the Cordilleran passive margin. New CA-TIMS zircon U-Pb age and whole-rock geochemical data from south-central Yukon, in concert with published studies from western Canada and United States, allow us to test the three possible rift models with different kinematic and igneous styles for the Cordilleran margin.

Pure-Shear Rift Models

Pure-shear rift models propose that Cordilleran lithosphere underwent uniform, homogeneous extension (McKenzie, 1978). Within this framework, Bond et al. (1985) used thermal subsidence curves to conclude that the final development of the Cordilleran passive margin occurred during a short-lived rift phase at the Ediacaran–Cambrian boundary. Christie-Blick and Levy (1989), however, noted the lack of evidence for late Ediacaran–early Cambrian crustal extension in locations with significant early Paleozoic subsidence. It follows that the field localities of Bond et al. (1985) were either inboard of the hinge zone between stretched and unstretched lithosphere or that pure-shear thinning is inappropriate and heterogeneous deformation and/or detachment faults may be important (Christie-Blick and Levy, 1989).

The timing of Cambrian–Ordovician magmatism, extension, and tectonic subsidence along the length of the Cordilleran margin, including that recorded by Kechika group, is not consistent with that predicted by pure-shear rift models. For example, there is no obvious mechanism to explain the timing of Tonian–Cryogenian rifting and basin development with respect to late Ediacaran and younger lithospheric breakup and magmatism (e.g., Yonkee et al., 2014). The marked asymmetry of the Cordilleran margin is also problematic for pure-shear rift models (Cecile et al., 1997), which typically predict symmetrical rift settings.

Simple-Shear Rift Models

Simple-shear or asymmetric rift models (Lister et al., 1986, 1991) assume that crustal-scale detachment faults result in upper- and lower-plate segments along continental margins. Cecile et al. (1997) and Lund (2008) used these ideas to conclude that Ediacaran–early Paleozoic subsidence trends and alkaline magmatism across lithospheric-scale lineaments in western Canada and United States were consistent with such asymmetric rifting models. For example, Ediacaran alkaline rocks associated with inboard (platformal) siliciclastic strata and erosional unconformities in British Columbia, Idaho, and Utah (e.g., Yonkee et al., 2014), are consistent with igneous underplating in an upper-plate margin setting. Lower Cambrian tholeiitic rocks in the outboard (basinal) regions of southern British Columbia (e.g., Kootenay terrane, Paradis et al., 2006) are furthermore consistent with lithospheric thinning and asthenospheric upwelling during lithospheric breakup (e.g., Lister et al., 1991; Lund,

2008). The spatial proximity of these mafic volcanic rocks with Cordilleran transfer-transform zones is consistent with inherited lineaments in modern rifts that accommodate along-axis flow of asthenospheric mantle-derived melts (Georgen and Lin, 2003; Bronner et al., 2011).

There are several outstanding problems in Cordilleran margin development that are not fully explained by simple-shear rift models. Firstly, simple-shear scenarios do not adequately explain how Tonian–Cryogenian rifting along western North America is related to the timing of Ediacaran–early Cambrian lithospheric breakup, similar to pure-shear rift models. Secondly, simple-shear rift models do not provide a mechanism to generate Cambrian–Ordovician alkaline magmas and accommodate coeval extension along the length of the margin after Ediacaran–early Cambrian lithospheric breakup and the onset of seafloor spreading. As a result, rift models for the Cordilleran margin must propose how post-breakup, lithospheric-scale processes occurred simultaneously in both upper- and lower-plate regions.

Depth-Dependent Rift Models

Modern passive margins are subdivided into magma-rich and magma-poor rift systems based on the volume of syn-rift magmatism, timing and location of lithospheric rupture, and lithospheric architecture (e.g., Franke, 2013; Doré and Lundin, 2015). Magma-poor rift margins have low volumes of syn-rift magmatism and undergo significant thinning through depth-dependent extension and necking of the crust and lithospheric mantle. The Newfoundland–Iberia system is the type example of a magma-poor rift and comprises a conjugate set of hyperextended, asymmetric margins that formed during the protracted

opening of the North Atlantic Ocean (e.g., Péron-Pinvidic et al., 2007, 2013; Péron-Pinvidic and Manatschal, 2009; Brune et al., 2014). Our preferred model follows the depth-dependent rift framework for the Newfoundland–Iberia system; below, we first present a comprehensive overview of North Atlantic rift evolution and then secondly propose corollaries for the Kechika group and other rock units along the Cordilleran margin using modern analogues to evaluate and further modify the hypotheses of Yonkee et al. (2014) and Beranek (2017). Although no two continental margin systems develop in an identical manner, the aim of our comparison is to summarize the relative timing and nature of sedimentary, magmatic, and plate tectonic processes that occurred during North Atlantic and Cordilleran rift evolution.

The initial Late Triassic to Early Jurassic crustal stretching phase of North Atlantic rift evolution (Fig. 14A) resulted in half-graben basins within the Grand Banks (offshore Newfoundland) and Lusitanian basin (onshore and offshore Portugal) platforms in the so-called proximal domain (Figs. 15A–15D; e.g., Péron-Pinvidic et al., 2013). These basins formed part of a major rift system that developed between Europe, Africa, and North America prior to the opening of the North and Central Atlantic (Klitgord and Schouten, 1986). South of the Newfoundland–Iberia rift system, the Central Atlantic Magmatic Province was emplaced at the Triassic–Jurassic boundary after initial rifting but prior to seafloor spreading (e.g., Marzoli et al., 1999; Nomade et al., 2007). The Central Atlantic Magmatic Province mostly consists of dikes and sills in Atlantic Canada, Iberia, and Morocco (e.g., Dunn et al., 1998; Verati et al., 2007).

After a period of thermal subsidence (Fig. 14A), renewed Late Jurassic–Early Cretaceous rifting and detachment faulting resulted in a necking domain or a region of major thinning (e.g., Unternehr et al., 2010; Péron-Pinvidic et al., 2013). The development of the necking domain was coincident Middle

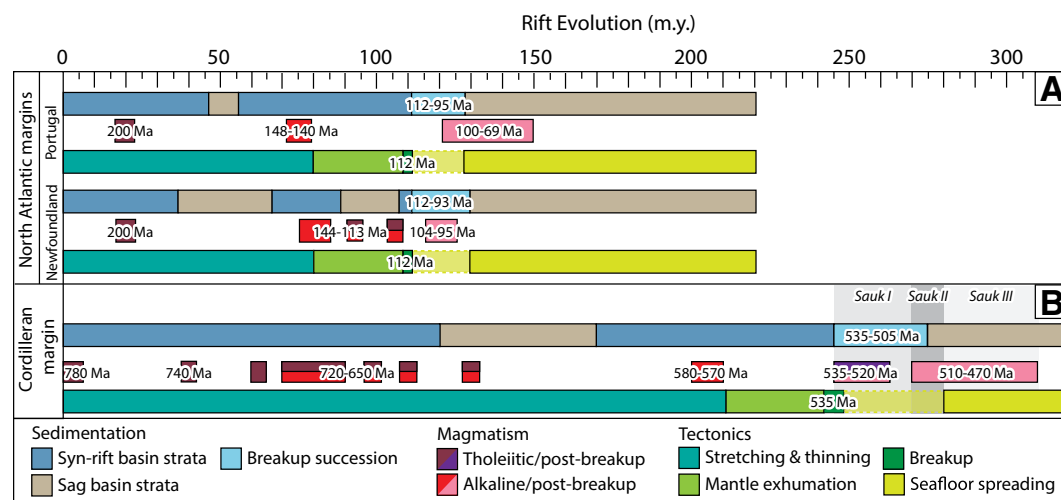


Figure 14. Rift evolution model showing the depositional, magmatic, and plate tectonic histories of the (A) North Atlantic and (B) Cordilleran margins modified from Beranek (2017).

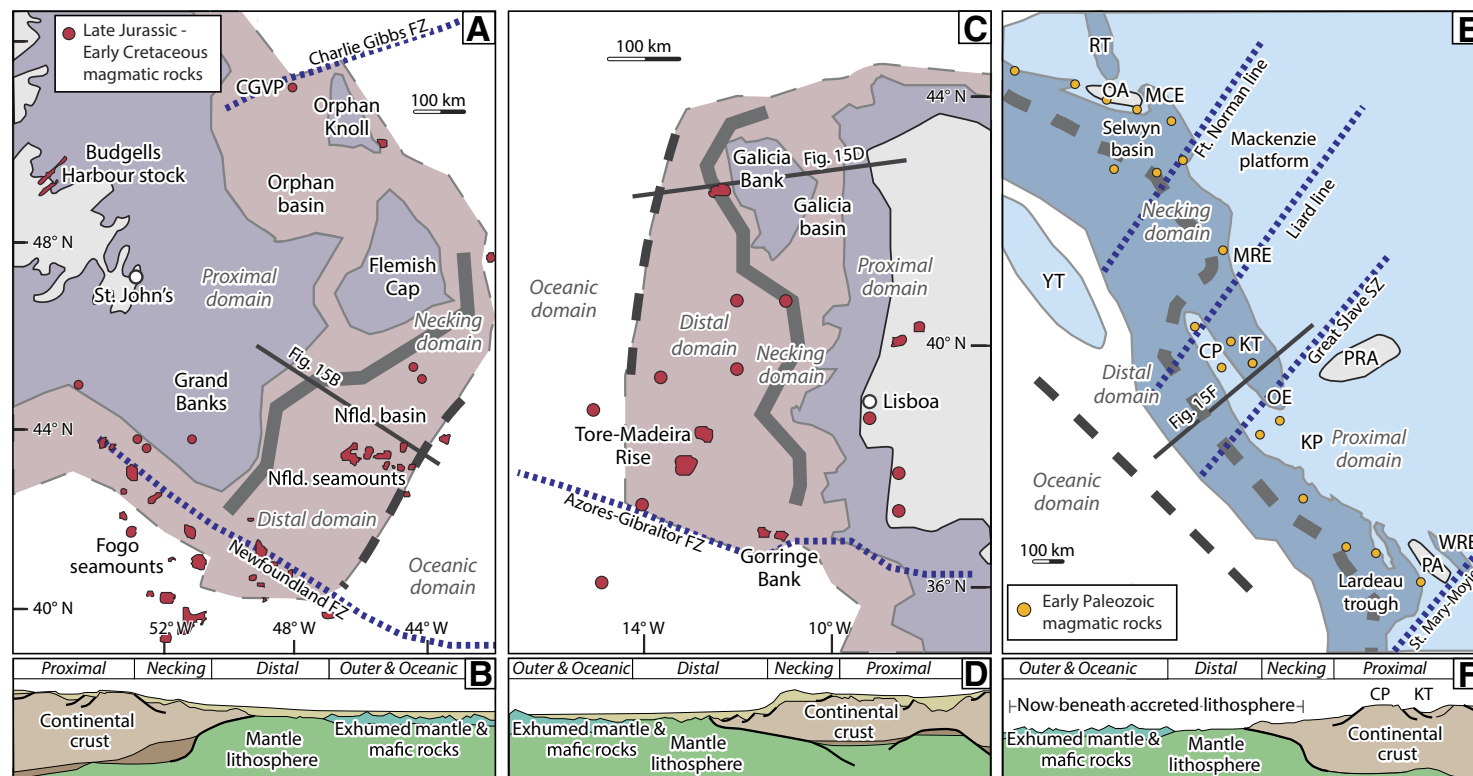


Figure 15. Continental margin maps and schematic cross sections of the (A, B) Newfoundland margin and (C, D) Iberian margin. Crustal architecture is adapted from Peron-Pinvidic et al. (2013) with the lighter and darker brown colors broadly referring to the distal and proximal portion of the margin, respectively. Late Jurassic–Early Cretaceous magmatic rock locations are from Pe-Piper et al. (2013). Solid gray line shows necking domain; dashed black line shows outer domain. Abbreviations: CGVP—Charlie Gibbs volcanic province; FZ—fracture zone. (E, F) Cartoon showing the magma-poor rift margin architecture of the late Cambrian–Early Ordovician Cordilleran margin. See text for interpretations. Framework geology is adapted from Cecile and Norford (1991), Cecile et al. (1997), and Pyle (2012). Restoration of the Tintina fault is from Gabrielse et al. (2006). Abbreviations: CP—Cassiar platform; KP—Kakwa platform; KT—Kechika trough; MCE—Misty Creek embayment; MRE—Meilleur River embayment; OA—Ogilvie Arch; OE—Ospika embayment; PA—Purcell arch; PRA—Peace River arch; RT—Richardson trough; WRE—White River embayment; YT—Yukon-Tanana terrane.

Jurassic–Early Cretaceous alkaline and ultrapotassic magmatism within the proximal domain (Figs. 15A–15D), including alkaline volcanic rocks in the Lusitanian basin (ca. 145 Ma; Grange et al., 2008) and Budgell Harbour Stock and related dikes in central Newfoundland (ca. 139–135 Ma; Helwig et al., 1974; Strong and Harris, 1974). Depth-dependent extension occurred as a result of shear zones in the weak middle crust (e.g., Wernicke, 1985; Lister et al., 1986; Lavier and Manatschal, 2006). These detachment faults likely reactivated long-lived basement weaknesses, such as rheological boundaries along preexisting basins (Masini et al., 2013; Manatschal et al., 2015). Detachment faulting within necking zones leads to the formation of a wedge of lesser extended crust, termed the H-block (hanging-wall) or keystone block, which is underlain by ductile lower lithosphere (e.g., Lavier and Manatschal, 2006; Péron-Pinvidic

and Manatschal, 2010). One of the H-block–bounding conjugate faults becomes preferentially weakened during strain softening and leads to the domination of one shear zone (Huisman and Beaumont, 2014). This process results in asymmetric, simple-shear rifting within the necking and distal domains and broadly resembles the upper- and lower-plate rift scenarios of Lister et al. (1986, 1991). Such rifting within relatively hot, pliable lithosphere widens the necking domain and leads to a complicated crustal configuration that includes failed rift or offset basins (Chenin and Beaumont, 2013; Manatschal et al., 2015). These v-shaped to margin-parallel basins (e.g., Orphan, Galician, and Porcupine basins) overlie thinned to locally ruptured lithosphere, are bounded by high-angle faults, and are associated with major lineaments such as the Charlie Gibbs fracture zone (e.g., Whitmarsh et al., 1996; O'Reilly

et al., 2006; Dafoe et al., 2017). These basins can result in partial or complete separation of the continental margin from outboard areas of thick crust, such as the Flemish Cap, Galicia Bank, and Orphan Knoll continental ribbons (Figs. 15A–15D; Péron-Pinvidic and Manatschal, 2010). The failure of these rift basins to proceed to lithospheric breakup has been linked to various causes, including zones of depleted subcontinental lithospheric mantle restricting the supply of magma (e.g., Manatschal et al., 2015) and as a function of the spreading rate (e.g., Doré and Lundin, 2015).

Early Cretaceous thinning led to hyperextended (<10-km-thick) crust and penetration of faults into the continental lithospheric mantle (e.g., Peron-Pinvidic et al., 2013). This resulted in coupled extension and Valanginian (ca. 140 Ma) and younger exhumation of continental lithospheric mantle along detachment faults (Fig. 14A; e.g., Boillot et al., 1980; Whitmarsh et al., 2001; Tucholke et al., 2007). The ocean-continent transition region is termed the distal domain and is variably composed of hyperextended crust, exhumed lithospheric mantle, embryonic oceanic crust, and magmatic intrusions (e.g., Peron-Pinvidic et al., 2013). Mantle exhumation was accompanied by the progressive emplacement of Lower Cretaceous (138–121 Ma) magmatic rocks toward the future site of breakup in the Gorringe and Galicia Bank areas, offshore Portugal (Figs. 14A and 15C; Schärer et al., 2000; Bronner et al., 2011; Eddy et al., 2017). Lower Cretaceous alkaline and tholeiitic rocks with N-MORB- to E-MORB-like signatures yield ϵ_{Hf} values that range from +12 to +20, comparable to modern rocks along this segment of the Mid-Atlantic ridge (+14 to +21; Blichert-Toft et al., 2005), suggesting derivation from the depleted asthenospheric mantle (e.g., Cornen et al., 1999; Schärer et al., 2000; Eddy et al., 2017). Coeval tholeiitic and lesser alkalic volcanic rocks in the Fogo Seamounts, offshore Newfoundland, have ϵ_{Nd} values that range from +1 to +6 and were emplaced along the Grand Banks leaky transform margin (e.g., Pe-Piper et al., 2007). These Nd-isotope values are lower than MORB along this segment of the Mid-Atlantic ridge (e.g., +7.5 to +11.5; Blichert-Toft et al., 2005). Pe-Piper et al. (2007) concluded that Upper Jurassic–Lower Cretaceous volcanic rocks were generated by edge-driven convection along the Grand Banks transform margin.

Aptian–Albian lithospheric breakup (Fig. 14A) was time-transgressive and occurred first in the south and migrated north (e.g., Bronner et al., 2011). Breakup was associated with the generation of a lithospheric breakup surface and overlying Albian–Cenomanian breakup succession (Fig. 14A) that records the transition from breakup tectonism to thermal subsidence (Soares et al., 2012). Syn-breakup activity included a large pulse of mafic magmatism in the distal domain (J-anomaly; Bronner et al., 2011) that was likely derived from the depleted mantle (Eddy et al., 2017). The delayed melt extraction may indicate that the lithospheric mantle acted as a sponge to melts derived from the upwelling asthenosphere (e.g., Müntener et al., 2010). Evidence for mafic magma emplacement within exhumed lithospheric mantle of the Newfoundland–Iberia rift system (e.g., Cornen et al., 1999; Müntener and Manatschal, 2006) and Alpine ophiolites (e.g., Müntener et al., 2010) supports this hypothesis.

Alkaline volcanic rocks with OIB-like signatures were emplaced along the Newfoundland–Iberia margins for at least 30 m.y. after Aptian–Albian lithospheric

breakup, prior to the first seafloor spreading magnetic anomaly ca. 84 Ma (Fig. 14A; Schärer et al., 2000; Hart and Blusztajn, 2006; Jagoutz et al., 2007). Wide-spread alkalic magmatism is a seemingly consistent feature along magma-poor rift margins (e.g., Manatschal and Müntener, 2009; Bronner et al., 2011). Post-breakup volcanism along the Newfoundland margin probably consisted of volcanic centers and sills that were spatially associated with transform-transfer faults and related margin-parallel faults. This includes the Newfoundland seamounts in the Newfoundland basin (Sullivan and Keen, 1977) and Charlie Gibbs Volcanic Province (Keen et al., 2014) and Orphan Knoll seamount (Pe-Piper et al., 2013) in the Orphan basin (Fig. 15A). The Charlie Gibbs Volcanic Province formed during the Late Cretaceous and was associated with extensional strain during oblique strike-slip movement along the Charlie Gibbs fracture zone (Fig. 15A; Keen et al., 2014). This structure likely allowed the upward migration of magma and acted as a transform margin separating the northern Orphan basin and volcanic-rich Rockall basin (Keen et al., 2014). The alkaline rocks of the Cretaceous Orphan Knoll seamount formed along a margin-parallel fault that provided a pathway for magmatism (Pe-Piper et al., 2013). Along the Iberian margin, mafic alkaline rocks of the Tore–Madeira Rise and onshore Portugal (Fig. 15C) have ϵ_{Hf} values that range from +4 to +12 (Merle et al., 2006, 2009; Miranda et al., 2009; Grange et al., 2010). These rocks formed through melting of an enriched mantle source that mixed with the subcontinental lithospheric mantle (e.g., Grange et al., 2010). Post-breakup volcanism generally consisted of alkaline, incompatible-element-enriched melts with intermediate isotopic values, in contrast to pre-breakup volcanic rocks, which suggests that lithospheric breakup exerted a significant control on the mantle sources and melting processes of subsequent magmatism along the continental margin.

The cause of post-breakup magmatism is uncertain, but the distribution of stress throughout the distal continental margin during the initiation of seafloor spreading (e.g., Jagoutz et al., 2007), continued thinning of the lithospheric mantle in distal basins (e.g., Dafoe et al., 2017), and influence of oblique-slip displacement along transfer-transform zones (e.g., Keen et al., 2014) are likely important factors. Within the Newfoundland–Iberia rift system, the lack of sufficient available melt prior to lithospheric breakup allowed the build-up of in-plane tensile stress along the nascent plate boundary (Tucholke et al., 2007). When this stress is suddenly released, termed tectonic spreading, it triggers a basin-wide extensional event that results in low-degree decompression melting and resultant off-axis magmatism (Jagoutz et al., 2007). Comparable processes likely occur during the initial production of oceanic crust and prior to the first seafloor-spreading magnetic anomaly (e.g., Bronner et al., 2011).

Modeling results from modern mid-ocean ridge systems suggest that some volatile and trace-element-rich melts sourced from upwelling asthenosphere undergo along-axis flow beneath the adjacent lithosphere (Keller et al., 2017). This would be consistent with seismic interpretations of melt at the lithosphere–asthenosphere boundary and provide an enriched metasomatized mantle source for alkalic, off-axis seamounts in modern margins (e.g., Niu et al., 2012; Keller et al., 2017). Although these ideas are developed on modern mid-ocean ridges, it is not inconceivable that similar metasomatic processes

occur along highly attenuated continental margins, especially during periods with evidence for tholeiitic magmatism. This would be consistent with post-breakup magmatic rocks in Portugal that resulted from the mixing of the subcontinental lithospheric mantle and an enriched asthenospheric mantle component (Grange et al., 2010).

The Neoproterozoic–early Paleozoic Cordilleran margin may have developed in a manner similar to that of the modern North Atlantic rift system (Yonkee et al., 2014; Hayward, 2015; Beranek, 2017). The early or Tonian–Cryogenian rift phase of Cordilleran development included intracratonic basin deposition (Windermere Supergroup), magmatism (780 Ma Gunbarrel event and 720 Ma to 660 Ma bimodal magmatism), and pure-shear stretching (Fig. 14A) that weakened an initially strong lithosphere relative to the cratonic interior (see also discussion and paleogeographic maps in Yonkee et al., 2014). We propose that this initial rift event is analogous to the Late Triassic–Early Jurassic stretching in the North Atlantic proximal domain, including that of the Grand Banks and Lusitanian basins. Whereas this North Atlantic phase apparently lasted ~50 m.y., the proposed equivalent in the Cordilleran proximal domain was >125 m.y. (Fig. 14A) and calls for a protracted intracratonic rift history that was influenced by the inherited structural, compositional, and thermal nature of western Laurentian lithosphere (e.g., Manatschal et al., 2015).

Ediacaran and early Cambrian rifting led to the initial development of the Kechika trough, Selwyn basin, Lardeau trough, and other basins with intermittent extensional histories (Gordey and Anderson, 1993; Logan and Colpron, 2006; Post and Long, 2008). This second rift stage lasted ~70 m.y. (Fig. 14B) and was probably related to formation of the necking zone (Figs. 15E and 15F) and significant lithospheric thinning, analogous to the development of outboard Jurassic–Cretaceous basins in the North Atlantic Ocean (e.g., Orphan basin; Dafoe et al., 2017). Cordilleran basins also likely evolved along transform-transfer zones and some outboard areas with periodic shallow-water deposition. Such outboard platforms, including the Cassiar platform, reflect lesser-extended crust and are likely comparable to continental ribbons such as the Flemish Cap (Figs. 15E and 15F). This is consistent with published observations for minimally extended, outboard crustal blocks in the northern Cordillera (Hansen et al., 1993; Cecile et al., 1997). Ediacaran alkaline volcanic rocks (Fig. 15E) of the Hamill Group in British Columbia (Colpron et al., 2002), Browns Hole Formation in Utah (Crittenden and Wallace, 1973), and lower Cambrian Quartet Mountain lamprophyre suite in northern Yukon (Milidragovic et al., 2006) are proposed equivalents to Jurassic alkaline and ultrapotassic volcanic rocks in the North Atlantic.

Lithospheric breakup along western Laurentia is widely thought to have occurred by the early Cambrian (e.g., Bond et al., 1984, 1985; see also discussion and paleogeographic maps in Yonkee et al., 2014). Recent studies have furthermore proposed that late Ediacaran–early Cambrian rift evolution involved heterogeneous mantle extension (Yonkee et al., 2014) that may have led to mantle exhumation and deposition of breakup successions like those along the modern North Atlantic margins (Fig. 14B; Beranek, 2017). Exhumed continental mantle blocks and hyperextended crust produced during late rift evolution are now located beneath accreted Cordilleran terranes (Fig. 15F; e.g.,

Hayward, 2015). Beranek (2017) predicted that a sequence boundary at the base of the Sauk I megasequence represents a lithospheric breakup surface along western North America. The breakup succession (Fig. 14B) includes early Fortunian to Cambrian Stage 5 strata (535–505 Ma) that from bottom to top consist of lowstand, transgressive, and highstand system tract deposits, similar to the Albian–Cenomanian (ca. 112–93 Ma) depositional histories offshore Portugal and Newfoundland (Soares et al., 2012).

Lower Cambrian volcanic rocks range in composition from tholeiitic to alkaline and broadly overlap with the inferred timing of breakup (Fig. 14B). Tholeiites in the Kootenay terrane near Shuswap Lake, southern British Columbia, yield N-MORB-like signatures and $\epsilon_{\text{Nd}t}$ values (+8; unit EBG of the Eagle Bay assemblage, Paradis et al., 2006) that are close to the predicted values for the Cambrian depleted mantle ($\epsilon_{\text{Nd}540} = +9.1$; Goldstein et al., 1984). Kootenay terrane strata that comprise sediment-sill complexes in the northern Selkirk Mountains (Index Formation) yield E-MORB- to N-MORB-like signatures and are locally associated with chlorite schist and serpentinized ultramafic rocks (e.g., Zwanzig, 1973; Logan and Colpron, 2006). Similar fault-bounded mafic and ultramafic units are associated with lower Cambrian volcanic and sedimentary rocks in the northern Kootenay terrane (Showshoe Group; e.g., Ferri and Schiarizza, 2006) and southern Kootenay terrane (e.g., Smith and Gehrels, 1992; Logan and Colpron, 2006). The juvenile mafic volcanic rocks, sediment-sill complexes, and association with Cu-rich base-metal deposits led Logan and Colpron (2006) to suggest a Gulf of California analogue for the Lardeau trough, implying that these rocks were emplaced during rift-related lithospheric thinning. Lardeau trough tholeiitic rocks are probably comparable to the depleted mantle-derived rocks that erupted during mantle exhumation and lithospheric breakup in the Gorringer, Galicia, and Grand Banks regions. Tholeiitic volcanism in the Kootenay terrane continued into the middle to late Cambrian (Ferri and Schiarizza, 2006; Logan and Colpron, 2006). Analogous to Early Cretaceous tholeiites in the Newfoundland-Iberia rift system, the emplacement of these Cambrian volcanic rocks and associated mafic to ultramafic intrusive rocks may have contributed to lithospheric heating and weakening. Other pre- to syn-breakup rocks that crop out between Ediacaran volcanic and clastic strata and lower Cambrian archaeocyathid horizons are expected to show depleted asthenospheric mantle contributions (e.g., Paradis et al., 2006). Lower Cambrian volcanic strata, however, are mostly exposed in the eastern or inboard regions of the Cordillera that may not have undergone sufficient lithospheric attenuation to expect only depleted mantle inputs. Example rock units include the Fish Lake volcanics (Donald Formation) of southern British Columbia (Kubli and Simony, 1992) and olivine basalt flows within the Prospect Mountain and Tintic Quartzites of Nevada and Utah (Morris and Lovering, 1961; Kellogg, 1963).

Upper Cambrian to Middle Ordovician volcanic strata, including the Kechika group presented here, form parts of the Sauk II, III, and Tippecanoe sequences (Fig. 14B), and their syn- to post-breakup nature is therefore suggestive of a magma-poor rift setting (e.g., Cecile et al., 1997; Beranek, 2017). Most Cambrian Series 2 to Ordovician volcanic rocks in Yukon and western United States are alkali basalts with OIB-like to E-MORB-like signatures (Fig. 16A).

Post-breakup volcanic rocks of the Kootenay terrane have lower overall LREE enrichment than volcanic rocks in other parts of the Cordilleran margin (Fig. 16A); however, they display geochemical trends consistent with increasing LREE enrichment and alkalinity following breakup. This is shown in British Columbia by the contrast between the Index Formation and overlying alkali basalts of the Jowett Formation (Logan and Colpron, 2006) and lower and upper parts of the Eagle Bay assemblage (Paradis et al., 2006), although this transition appears slightly more complex within Cambrian volcanic strata of the Snowshoe Group (e.g., Ferri and Schiarizza, 2006). Within the upper section of the Eagle Bay assemblage, Cambrian Series 2 alkali basalts yield intermediate ϵ_{Nd} values (range from +4 to +6; Paradis et al., 2006), which suggest the involvement of incompatible-element-enriched mantle following breakup. The generation of syn- to post-breakup alkaline volcanic rocks along western North America is akin to the emplacement of post-Aptian magmatic rocks on both sides of the Newfoundland-Iberia rift, including those near Orphan Knoll and Galicia Bank (Figs. 16A and 16B; e.g., Jagoutz et al., 2007; Bronner et al., 2011). Notably, many occurrences of post-breakup magmatic rocks along the Cordilleran and Newfoundland-Iberia margins are spatially associated with leaky transfer-transform lineaments and extensional faults. These structures are likely important for localizing basin-wide extension and associated off-axis magmatism (Jagoutz et al., 2007). Therefore, the lack of sufficient melt to enable breakup and initiate seafloor spreading within a magma-poor rift system could directly explain the wide distribution and longevity of syn- to post-breakup magmatism along both rifted margins. The major distinction in magmatism that follows lithospheric breakup is an increase in the proportion of alkaline volcanic rocks with contributions from an enriched mantle source.

Implications for Peri-Laurentian Terrane Evolution

Many observations of the North Atlantic Ocean basin, including the presence of hyperextended crust and exhumed lithospheric mantle, are preserved in deep-water regions that represent the necking and distal domains of the Newfoundland-Iberia rift. In the North American Cordillera, such elements are structurally beneath accreted allochthons (Hayward, 2015; Beranek, 2017), but we propose that outer continental margin remnants may be preserved in both parautochthonous and allochthonous fragments with ties to the western Laurentian margin. For example, the Yukon-Tanana terrane (Fig. 1) is demonstrably of peri-Laurentian affinity, but its pre-Late Devonian magmatic and tectonic histories are uncertain (e.g., Colpron et al., 2007). In central Yukon, the exposed metasedimentary basement of Yukon-Tanana (Snowcap assemblage) includes amphibolite units with OIB- to E-MORB-like signatures, ϵ_{Nd} and ϵ_{Hf} values that indicate an enriched mantle source, and Proterozoic depleted mantle model ages (Piercey and Colpron, 2009). These amphibolites are analogous to Neoproterozoic to lower Paleozoic mafic rocks of the Cordilleran margin (Piercey and Colpron, 2009), including alkaline to tholeiitic rocks of the parautochthonous Kootenay terrane and Kechika group. The chondritic to superchondritic

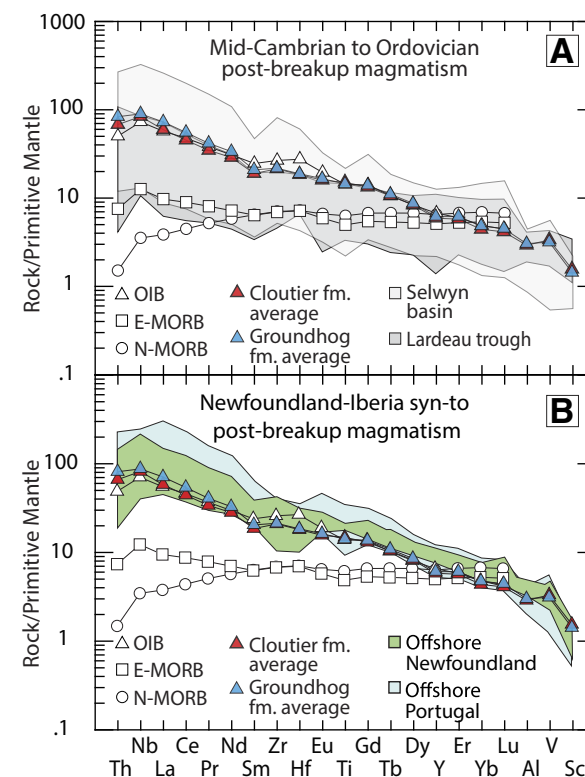


Figure 16. Primitive mantle-normalized multi-element plots of mafic rock units. (A) Kechika group average (this study), mid-Cambrian to Ordovician rocks of the Lardeau trough and Selwyn basin, and global averages for ocean-island basalt (OIB) and normal and enriched mid-ocean ridge basalt (N-MORB and E-MORB). Primitive mantle values and global averages are from Sun and McDonough (1989) and McDonough and Sun (1995). The Lardeau trough units include the Index and Jowett Formations (Logan and Colpron, 2006), Frank Creek volcanics (Ferri and Schiarizza, 2006), and Eagle Bay assemblage rocks that overlie the Cambrian Tshinakin limestone (Paradis et al., 2006). The Selwyn basin units include the Marmot Formation (Leslie, 2009), Menzie Creek formation (Pigage, 2004), and Crow, Rabbitkettle, and Sunblood Formations (Pigage et al., 2015). (B) Cretaceous syn- to post-breakup volcanic rocks of the Newfoundland margin include the Ocean Drilling Program site 1276 (Hart and Blusztajn, 2006) and Orphan Knoll seamount (Pe-Piper et al., 2013). Cretaceous syn- to post-breakup Iberian margin rocks include the western Iberian continental margin (Miranda et al., 2009) and the Tore-Madeira Rise (Merle et al., 2009).

Nd- and Hf-isotope signatures of metamorphosed carbonate rocks intercalated with the amphibolites have been used to infer emplacement during a major magmatic pulse, such as the Gunbarrel magmatic event (e.g., Piercey et al., 2006). If early Cambrian lithospheric breakup along western Laurentia was accompanied by an outboard magmatic pulse, comparable to that of the

Aptian–Albian magmatic pulse along the Newfoundland–Iberia rift system (Bronner et al., 2011), then some Yukon–Tanana basement rocks may instead have ties with the lower Cambrian syn-breakup successions of northwestern Laurentia. It follows that Yukon–Tanana (YT in Fig. 15E) and potentially other peri-Laurentian terranes may have originated as basement highs or continental ribbons outboard of the Cordilleran margin.

CONCLUSIONS

Cambrian–Ordovician igneous rocks of the Pelly Mountains, south-central Yukon, have zircon U–Pb crystallization ages and geochemical compositions that provide new constraints on the tectonic significance of post-breakup magmatism in western North America. Comagmatic gabbro and basalt units of the Kechika group that postdate lithospheric breakup by >40 m.y. were generated by the low-degree partial melting of enriched mantle and emplaced within submarine volcanic centers and sill-sediment complexes during margin-scale extension. The Liard line, a long-lived basement feature that defines a transfer-transform zone in the northern Canadian Cordillera, likely accommodated Cambrian–Ordovician magmatism in the Pelly Mountains and adjacent areas of southeastern Yukon and northern British Columbia. Our preferred model for Cordilleran rift evolution features a depth-dependent rift scenario like that of the Newfoundland–Iberia system and includes Tonian–Cryogenian stretching and thinning, late Ediacaran–early Cambrian mantle exhumation and tholeiitic-dominated breakup magmatism, and middle Cambrian to Ordovician alkaline-dominated post-breakup magmatism. The Kechika group likely originated in a manner akin to mid- to Late Cretaceous sills and seamounts within the distal margins of Newfoundland (e.g., Orphan Knoll) and Portugal (e.g., Galicia Bank, Tore–Madeira Rise). Following the models of Tucholke et al. (2007) and Jagoutz et al. (2007), it is predicted that the Kechika group and related off-axis volcanic units were generated during the release of in-plane tensile stresses after lithospheric breakup but prior to the establishment of a spreading ridge and formation of new ocean crust along northwestern Laurentia.

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