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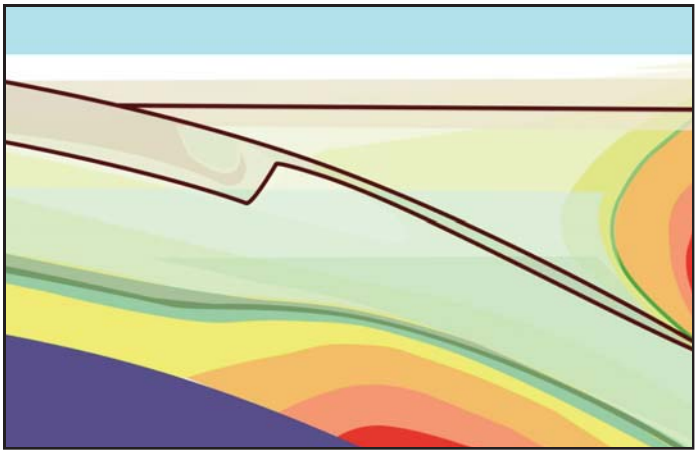

Stratigraphy and U–Pb Zircon–Titanite Geochronology of the Aley Carbonatite Complex, Northeastern British Columbia: Evidence for Antler-Aged Orogenesis in the Foreland Belt of the Canadian Cordillera

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SUMMARY

The tectonic significance and age of carbonatite intrusions in the central Foreland Belt of the Canadian Cordillera are poorly constrained. Recent work has demonstrated that one of these carbonatite intrusions, the Aley carbonatite, was emplaced as a syn-kinematic sill, coeval with a major nappe-forming tectonic event. Determining the age of the Aley carbonatite thus provides a means of directly dating syn-tectonic magmatism. Attempts at dating carbonatite units failed due to low U–Pb content in sampled zircon; however, a U–Pb titanite age of 365.9 ± 2.1 Ma was obtained from the Ospika pipe, an ultramafic diatreme spatially and genetically related to the carbonatite. This U–Pb titanite age is further supported by respective ^{40}Ar/^{39}Ar phlogopite ages of 359.4 ± 3.4 Ma and 353.3 ± 3.6 Ma for the pipe and a spatially associated lamprophyre dyke. We interpret the Late Devonian U–Pb titanite age of the Ospika pipe to be the minimum possible age of the carbonatite and syn-magmatic nappe-forming tectonic event. The maximum possible age of the carbonatite is constrained by the Early Devonian age of the Road River Group, the youngest strata intruded by carbonatite dykes and involved in the nappe-forming event. Our dating results for the Aley carbonatite closely correlate with U–Pb zircon and perovskite ages obtained for the Ice River carbonatite complex in the central Foreland Belt of the southern Canadian Cordillera, and support the interpretation of carbonatite intrusions of the western Foreland Belt as genetically linked components of an alkaline-carbonatitic magmatic province. Structural, stratigraphic, and geochronological data from the Aley area indicate that deformation was similar in style to, and coeval with, structures attributable to the Antler orogeny, and are consistent with the Antler orogen having extended the length of the Cordilleran margin from the southern United States to Alaska.

RÉSUMÉ

La signification tectonique et l'âge des intrusions de carbonatite dans le Domaine de l'avant-pays central de la Cordillère canadienne sont méconnus. Des travaux récents ont démontré qu'une de ces intrusions de carbonatite, la carbonatite d'Aley, a été mise en place en tant que filons-couches syn-cinématiques, contemporains avec un événement tectonique majeur de formation de nappe. La détermination de l'âge de la carbonatite d'Aley fournit ainsi un moyen de datation directe du magmatisme syn-tectonique. Les tentatives de datation des unités de carbonatite ont échoué en raison de la faible teneur en U – Pb du zircon échantillonné; cependant, un âge U–Pb de 365,9 ± 2,1 Ma a été obtenu à partir de titanite provenant de la cheminée d'Ospika, une diatrème ultramafique spatialement et géné-

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tiquement apparenté à la carbonatite. Cet âge U–Pb sur titanite est en outre soutenu par des âges $^{40}Ar/^{39}Ar$ sur phlogopite de 359,4 ± 3,4 Ma et 353,3 ± 3,6 Ma respectivement pour la cheminée et un dyke de lamprophyre spatialement associé. Nous interprétons l'âge U–Pb des titanites du Dévonien supérieur de la cheminée d'Ospika comme étant l'âge minimum possible de la carbonatite et de l'événement tectonique syn-magmatique de formation de nappe. L'âge maximum possible de la carbonatite est limité par l'âge Dévonien inférieur du groupe de Road River, les plus jeunes strates traversées par les intrusions de dykes de carbonatite et impliquées dans l'événement de formation de nappe. Nos résultats de datation pour la carbonatite d'Aley sont étroitement corrélés avec les âges U–Pb sur zircon et pérovskite obtenus pour le complexe de carbonatite de Ice River dans le Domaine de l'avant-pays méridional de la Cordillère canadienne, et appuient l'interprétation des intrusions de carbonatite du Domaine de l'avant-pays occidental comme étant des composantes génétiquement liés d'une province magmatique alcalino-carbonatitique. Les données structurales, stratigraphiques et géochronologiques de la région d'Aley indiquent que la déformation était semblable et contemporaine aux structures attribuables à l'orogenèse Antler, et sont compatibles avec l'orogène Antler ayant étendu la longueur de la marge de la Cordillère depuis le sud des États-Unis États jusqu'en Alaska.

INTRODUCTION

Paleozoic strata in the western Foreland Belt of the Canadian Cordillera are characterized by widely spaced carbonatite and silica-undersaturated alkali intrusive and volcanic complexes (Fig. 1). A detailed structural study of one of the carbonatite complexes, the Aley carbonatite of the Rocky Mountains of northeastern British Columbia (McLeish and Johnston 2019) demonstrated that the carbonatite: (1) forms a sill intruded near the base of a lower to middle Paleozoic stratigraphic sequence that includes, from oldest to youngest, the Kechika and Skoki formations and the Road River Group; and (2) is, together with its wall rocks, overturned, forming the lower limb of a syn-magmatic crustal-scale recumbent nappe. McLeish and Johnston (2019) interpreted the carbonatite and syn-magmatic nappe as manifestations of the Antler collisional orogeny along an active convergent margin.

General questions arising from these findings include: (1) are other Cordilleran carbonatite complexes attributable to the same collisional event; (2) was the collisional orogenic event of continental scope; and, if so (3) can we distinguish correlative structures and identify sedimentary, igneous and metamorphic rocks attributable to the same event elsewhere in the foreland of the Cordillera? Answering these questions requires that we constrain the timing of deformation and syn-kinematic magmatism in the Aley region. Toward this goal, we conducted an integrated field stratigraphic and geochronological study of the Aley carbonatite complex and its wall rocks, including a post-kinematic diatreme, the Ospika pipe; the Lady Laurier volcanic unit, part of the Ordovician Skoki Formation; and a volcano-sedimentary member of the Kechika Formation. Specific questions addressed include: (1) what is the age of intrusion of the syn-kinematic Aley carbonatite and by extension the timing of nappe formation; (2) what is the temporal relationship between the spatially associated silica-undersaturated to alkalic Aley carbonatite, Ospika pipe diatreme, lamprophyre dykes and Lady Laurier (Skoki Formation) volcanic unit; and (3) when was the onset of magmatism, as recorded by the volcano-sedimentary member of the Kechika Formation, in the Aley region of the western Foreland Belt? Here we review the geological setting of the Aley carbonatite and its wall rocks, present the results of our geochronological studies, and attempt, using these data, to address these questions.

GEOLOGY OF THE ALEY REGION OF THE ROCKY MOUNTAINS OF NORTHEASTERN BRITISH COLUMBIA

General Information

The study area lies within the Williston Lake area of the western Foreland Belt of the Rocky Mountains and is characterized by lower to middle Paleozoic deep water carbonate rocks and shale (Figs. 1 and 2). These units consist of slope to off-shelf deep-water strata and define the paleogeographic Kechika Trough (Pyle and Barnes 2003). In the Aley region, the north–south trending, 50 km-wide trough is bounded to the west by the Northern Rocky Mountain Trench, which is host to an Eocene dextral strike-slip fault interpreted to have accommodated > 400 km of dextral strike-slip displacement (Gabrielse 1985), and to the east by a facies boundary defined by the western limit of shallow water carbonate rocks of the MacDonald Platform (Aitken 1971; Pyle and Barnes 2003). This facies boundary constitutes the boundary between the western and eastern subprovinces of the Foreland Belt (Fig. 2). North of 59°N latitude, the Kechika Trough widens into the Selwyn Basin. The trough terminates immediately south of the Aley region, where the facies boundary marking the eastern margin of the trough curves around to the west, and is truncated against the Northern Rocky Mountain Trench fault. Thompson (1989) established the regional stratigraphic framework of the MacDonald Platform and Kechika Trough. Additional stratigraphic studies of the Aley region include Pride (1983) and Pyle and Barnes (2001). Intrusive into the Kechika Trough stratigraphic sequence are the Aley carbonatite, the Ospika pipe diatreme and lamprophyre dykes (Fig. 2). In addition to these intrusive rocks, igneous activity in the Kechika Trough is marked by the 10–100 m-thick Lady Laurier volcanic member of the Skoki Formation. Within the study area, the stratigraphic sequence and the Aley carbonatite intrusion all lie within and define the overturned lower limb of a crustal scale nappe (Fig. 3; McLeish and Johnston 2019).

Structural History of the Study Area

Detailed 1:5000 scale mapping of the carbonatite and Paleozoic host stratigraphy reveals a complex polyphase deformation record preserved within the elliptical complex (McLeish and Johnston 2019). Deformation is manifested by early isoclinal folding and associated shearing (D_1) of mineralized apatite and magnetite-rich laminations within the carbonatite, and the development of isoclinal folds (F_1), a bedding parallel (axial

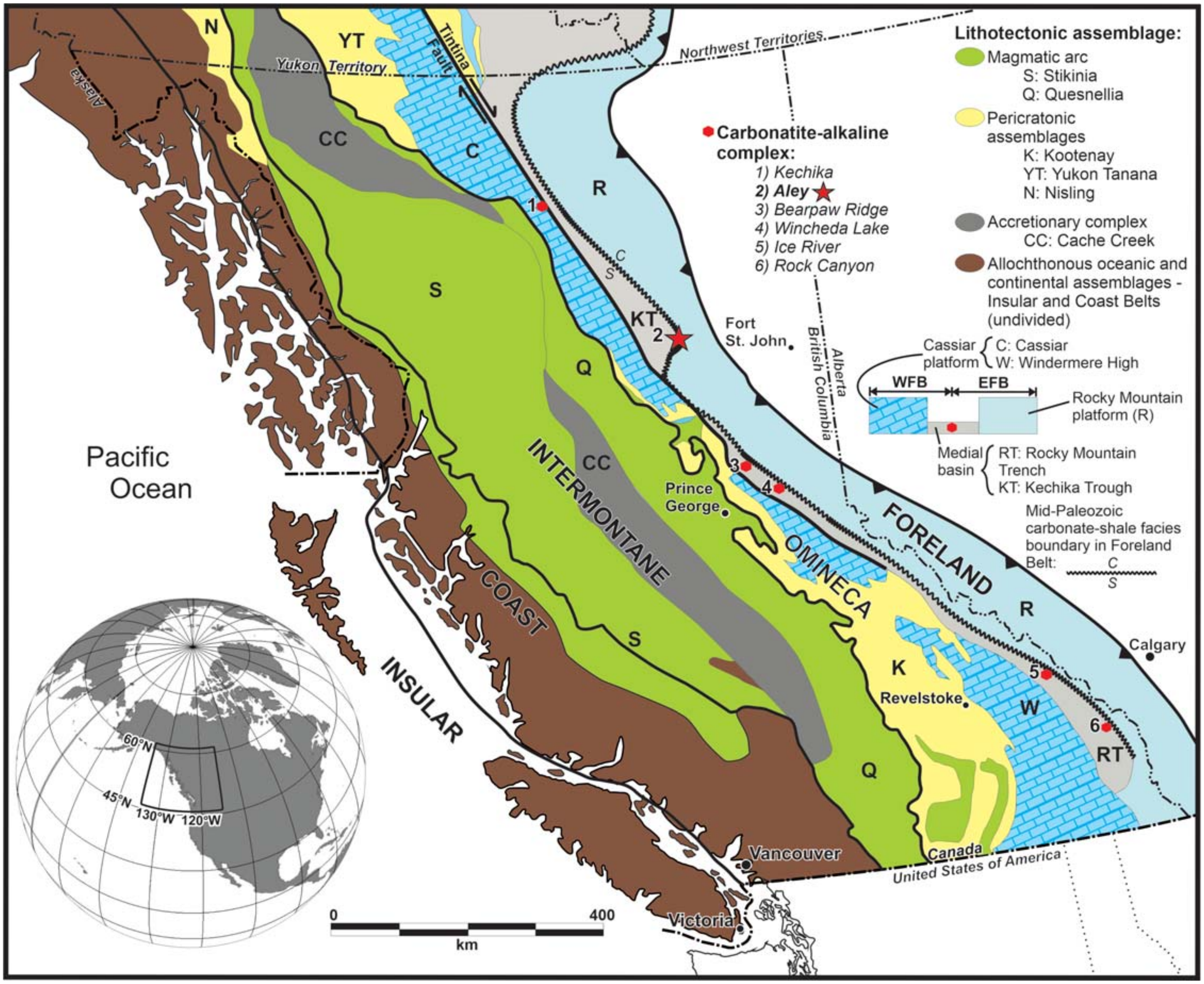

Figure 1. First-order morphological subdivisions of the Canadian Cordillera with known Foreland Belt alkaline-carbonatite complexes shown in reference to the transition of early Paleozoic continental platform and slope facies to deep-water basinal facies. This transition is also known as the Carbonate-to-Shale, or C–S, boundary, and is interpreted to separate the western and eastern divisions of the Foreland Belt (WFB and EFB, respectively). Alkaline complex localities in part after Pell (1994); facies boundary after Wheeler and McFeely (1991). The distribution of Paleozoic alkaline volcanic rocks in the Foreland Belt (not shown) closely mirrors that of the carbonatite complexes. Figure after McLeish and Johnston (2019).

planar) cleavage (S_1), and low-angle thrust faults within the host stratigraphy. Fabrics generated by the D_1 event have been transposed by asymmetric, large-amplitude cascading and chevron-style folds (F_2) of the Rocky Mountain orogeny (D_2); fold interference between these two deformation events has led locally to the development of mineral fabrics trending approximately E–W, orthogonal to the regional Rocky Mountain trend.

The Geology of the Antler Orogen

Roberts (1951) first recognized and defined the Antler orogen in southern Idaho and central Nevada. The Late Devonian to Mississippian orogeny involved the eastward emplacement of Cambrian–Devonian sedimentary rocks onto the western margin of the Laurentian craton. The timing of the orogeny is constrained by the oldest (latest Devonian) allochthon-derived synorogenic strata and Late Mississippian successor passive margin strata which unconformably overlie the synorogenic strata (Trexler et al. 2004). Previous to this study, no plutonic rocks have been associated with the Antler orogen, and no occurrences of Antler-aged high-grade metamorphic rocks are known (see Speed and Sleep 1982; Burchfiel and Royden 1991; Linde et al. 2017). It is thought that the Antler magmatic arc was largely or entirely subducted during arc–continent collision (Speed and Sleep 1982).

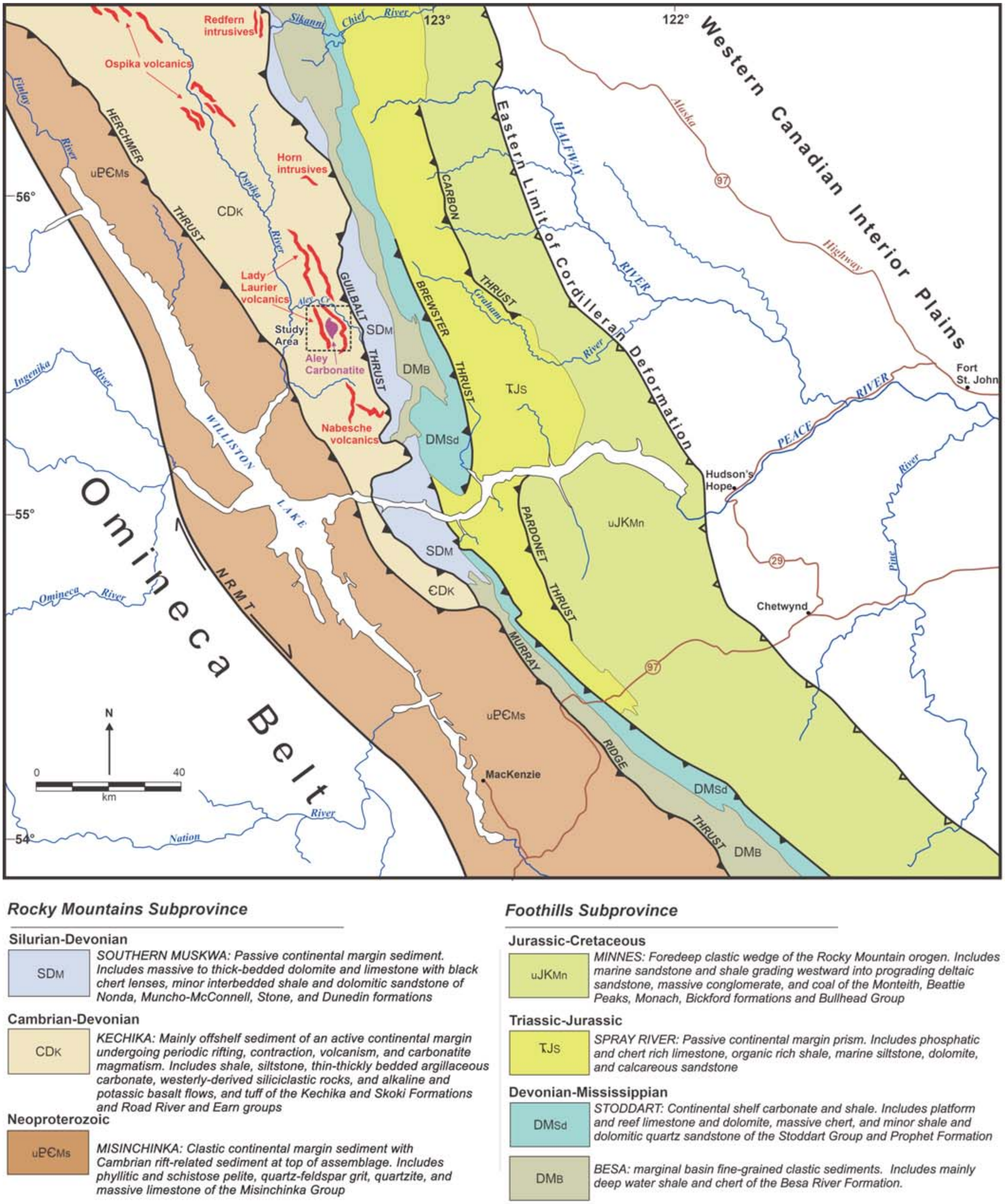

Figure 2. Simplified geological map of the Williston Lake area of northeastern British Columbia showing key tectono-stratigraphic divisions (after Wheeler and McFeely 1991). Several alkaline volcanic occurrences (red) and the Aley carbonatite complex (purple) define a strike-parallel belt of Paleozoic igneous activity unseen in Paleozoic continental shelf and margin strata to the east. The location of the carbonate-to-shale facies boundary (not shown) of Wheeler and McFeely (1991) roughly coincides with the Guilbalt Thrust. Note, due to the simplification of geological units on this map, the unit abbreviations and areas covered by the units in this figure differ slightly from Figure 3. NRMT = Northern Rocky Mountain Trench.

STRATIGRAPHIC UNITS

Kechika Formation (Late Cambrian to Early Ordovician)

Within the study area, the Kechika Formation is divisible into a lower volcano-sedimentary member, and an upper carbonate and siliciclastic member (McLeish 2013). The heterogeneous lower volcano-sedimentary member consists of interlayered conglomerate, pillow basalt, tuff, volcaniclastic rocks and fragmental volcanic layers. The pebble to boulder conglomerate layers are discontinuous and are of variable thickness. Quartzite, siltstone, granitoid rock and dolostone clasts are rounded to well-rounded. Volcanic layers weather dark to light green. Well preserved pillows are rare; fragmental volcanic layers, tuff and immature, volcaniclastic sedimentary rocks are more common. The exposed thickness of this member in the study area is 200 m. Its total thickness is difficult to constrain as its base has been intruded by the Aley carbonatite, and no pre-Kechika strata are exposed in or adjacent to the study area. Correlative volcanic layers within the lower Kechika Formation (Fig. 2) have been documented 100 km north of the Aley region in the Redfern Lake (Taylor and Stott 1973; Taylor 1979) and Ospika River areas (Taylor et al. 1979; MacIntyre 1998).

Carbonate and siliciclastic strata of the upper sedimentary member of the Kechika Formation include tan-brown and grey planar laminated argillaceous limestone; wavy, banded orange-brown calcareous siltstone; and massive, cream-coloured dolostone. These strata are interpreted to have been deposited in a deep-water, slope to off-shelf environment (Pyle and Barnes 2001). Siliciclastic strata are phyllitic, have a bedding-parallel cleavage, and record low-grade metamorphism. The maximum thickness of the upper member in the map area is 800 m (Fig. 3D).

Age constraints on the Kechika Formation are few. No direct age constraints on the volcano-sedimentary member in the study area are available; however, correlative volcanic strata of the Kechika Group in the Pelly Mountains of south-central Yukon yield Cambrian to Ordovician zircon U–Pb ages (Campbell et al. 2019). Few fossils are preserved in the upper sedimentary member. Pride et al. (1986) and Mader (1986) labelled the Kechika Formation within the study area as Cambrian, whereas Thompson interpreted the age of the formation to extend into the Early Ordovician; conodonts recovered from the uppermost member to the north of the Aley region indicate an Early Ordovician age (Pyle and Barnes 2001).

Skoki Formation (Early to Late Ordovician)

The Skoki Formation is divisible into lower and upper dolostone members that are separated by a distinct volcanic member informally referred to as the Lady Laurier volcanic unit (Mader 1986; McLeish 2013). The dolostone members consist of cliff-forming, grey weathering, medium to thick-bedded, mottled grey dolostone. Relict primary textures show that the dolostone originally consisted of massive to cross-bedded bioclastic limestone. Fossiliferous layers contain crinoid ossicles, gastropods and, in the upper dolostone member, planispiral (*Maclurites*) gastropods (Mader 1986). Chert lenses and oncolites are rare in the lower dolostone member, but are common toward the top of the upper dolostone member adjacent to the contact with the stratigraphically overlying Road River Group.

Argillaceous, wavy bedded dolostone is present in the lower dolostone member near the contact with the underlying Kechika Formation. The contact between the lower member and the Kechika Formation is commonly faulted; low angle faults that developed along the overturned lower limb of the nappe during nappe formation cut structurally down-section, stratigraphically up-section, from the upper Kechika Formation into the lower dolostone of the Skoki Formation, thinning the overturned stratigraphic sequence (McLeish and Johnston 2019). The thickness of the lower dolostone member is estimated to be 150 m based on exposures in the northwest of the study area where the lower contact with the Kechika is little modified by faults and the contact with the volcanic member is sharp. The thickness of the upper dolostone member is 200 m as constrained by a complete section exposed in the southeast of the study area (Fig. 3D).

The 10- to 100 m-thick middle (Lady Laurier) volcanic member of the Skoki Formation consists of fine-grained submarine volcanic lapilli-to ash-tuff that passes upward into agglomerate and volcaniclastic layers. Metre-thick layers of dark green shale are common, whereas pillow basalt is rare. Carbonatite ocelli have been observed in agglomeratic layers (D. Canil personal communication 2009). Dolostone layers interfinger with volcanic layers near the top of the volcanic member, and the contact with the overlying dolostone is gradual. Structurally thinned (10–20 m) exposures of this member are common. The Skoki Formation, including the Lady Laurier volcanic member, is continuous throughout the Halfway River region (Thompson 1989). Paleontological studies constrain the age of the formation to Early to Late Ordovician (Cecile and Norford 1979; Thompson 1989; Pyle and Barnes 2001). No direct age determination is available for the volcanic member.

Road River Group (Late Ordovician to Early Devonian)

The Road River Group consists of a > 1 km-thick sequence of off-shelf clastic and lesser carbonate rocks. The contact with the Skoki Formation is sharp, possibly unconformable, and is marked by an abrupt transition from thickly bedded, resistant, chert-rich dolostone to recessive shale. Within the study area, the Road River Group can be divided into two shale-dominated members that are separated by a quartzite unit (McLeish 2013). The lower member consists of fissile, graptolitic shale and planar-laminated to thinly bedded, grey-weathering siltstone and argillaceous limestone. At least four, 10–20 m-thick quartzite beds are present 175 to 300 m above the contact with the underlying Skoki Formation. The quartzite beds are massive, fine- to medium-grained and homogeneous, and form a distinctively resistant section that can be traced throughout the map area; they were recognized regionally as a distinct unit by Thompson (1989). The upper member consists of graptolitic shale and laminated siltstone, but also contains metre-thick dolostone beds with chert lenses. Pride (1983) described an additional dolomitic quartzite unit at the top of the Road River Group. Paleontological collections of Cecile and Norford

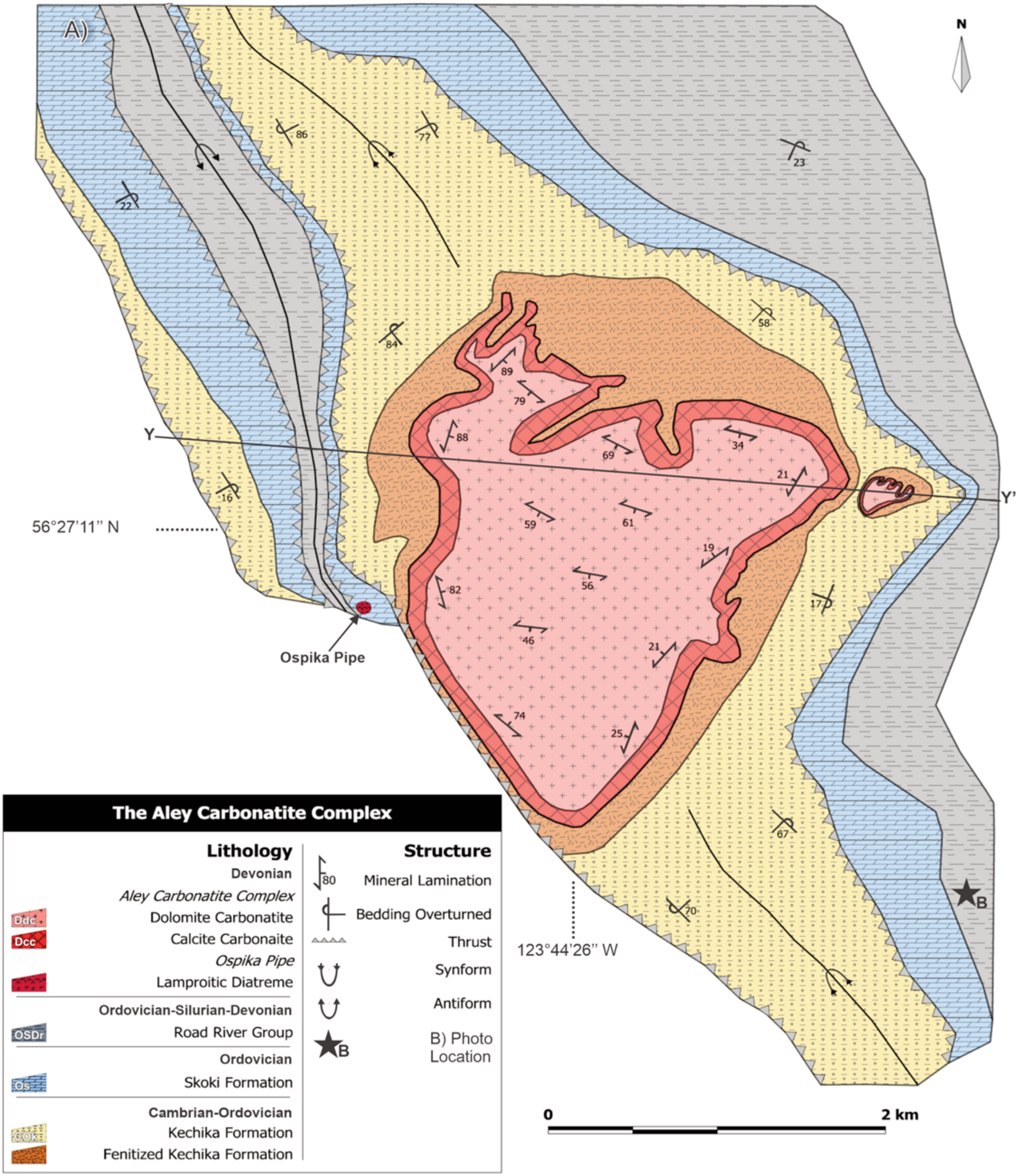

Figure 3. (A) Geological map of the Aley carbonatite complex (in part, after Mader 1986 and McLeish and Johnston 2019).

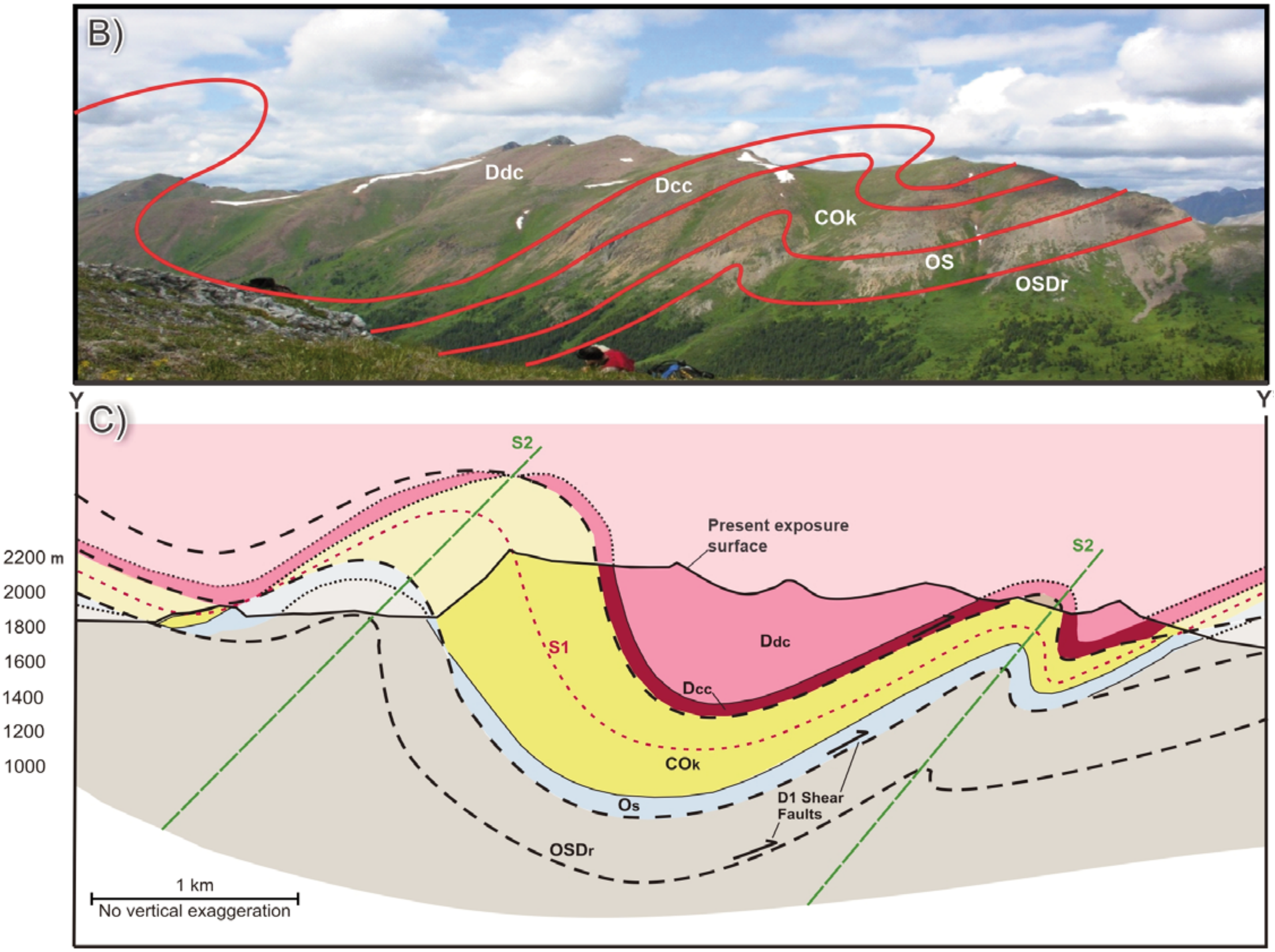

Figure 3. *cont'd* (B) East-west profile view of the Aley carbonatite complex showing the distribution of the major map units (after McLeish and Johnston 2019); (C) Geological cross-section Y-Y' from Figure 3A (after McLeish and Johnston 2019). See Figure 3A legend for explanation of rock units. Note, the location of the fenitized Kechika Formation is not shown on the cross-section due to the generally narrow but variable width of the unit.

(1979) and Norford (1979) indicated the age range of the Road River Group in the region to be Late Ordovician to Early Devonian.

INTRUSIVE ROCKS

Exposures of intrusive rocks in the Aley Creek area include: (1) the Aley carbonatite sill; (2) the Ospika diatreme pipe; and (3) ultrabasic lamprophyre dykes and sills (Fig. 3). The carbonatite has been described by Pride (1983, 1987a, b), Mader (1986), Pell (1994), Chung & Crozier (2008), Crozier (2011, 2013), and Chakhmouradian et al. (2015).

Aley Carbonatite

The Aley carbonatite intruded as a 1.5 km-thick, layer-parallel sill into or at the base of the lower volcanic member of the Kechika Formation (McLeish and Johnston 2019). The carbonatite now lies structurally above the host stratigraphic sequence and is preserved in the core of an asymmetric, Rocky Mountain deformation-related F_2 synform. The synform verges east, with a steeply dipping to vertical west limb, a shallowly west-dipping east limb and a moderately west-dipping axial surface (Fig. 3). To the east, 0.5 km from the eastern margin of the main exposure, a separate 300-metre-wide exposure of the carbonatite sill crops out in a smaller parasitic F_2 synform. Three principal units within the carbonatite have been identified: (1) a volumetrically dominant fersmite- and pyrite-bearing dolomite–apatite carbonatite unit that forms the core of the sill; (2) a magnetite, pyrochlore, phlogopite-bearing calcite-apatite carbonatite unit that forms the top of the sill where it is in contact with the Kechika Formation; and (3) a banded magnetite-apatite unit in the dolomite core (Kressall et al. 2010).

Variably developed apatite mineral bands within the calcite and dolomite carbonatite units define a layer-parallel S_1 foliation interpreted to have developed during, and provides a record of, D_1 plastic flow (McLeish et al. 2010). The S_1 foliation in the carbonatite is concordant with the bedding-parallel S_1 cleavage in the country rock and is cut and truncated by late phase dolomite carbonatite dykes, indicating that intrusion of the carbonatite was syn-kinematic with D_1 nappe formation (McLeish and Johnston 2019). The banded magnetite–apatite unit is conformable with the S_1 fabric and may represent a distinct primary cumulate phase of the carbonatite. Locally, calcite and dolomite carbonatite units contain xenoliths of heavily fenitized siltstone country rock, likely belonging to the Kechika Formation. The abundance of xenoliths increases towards the top margin of the sill, with the peripheral calcite carbonatite unit containing the highest concentration. Numerous dykes and sills of calcite and dolomite carbonatite intrude the Kechika Formation in the fenitized contact aureole where cross-cutting relationships show that the calcite carbonatite preceded intrusion of the dolomite carbonatite (McLeish and Johnston 2019).

A metasomatic fenite aureole extends up to 1 km (apparent thickness) out from the carbonatite–Kechika Formation contact into the upper sedimentary member of the Kechika Formation (Fig. 3). Fenite metasomatism (fenitization) is indicated by replacement of the primary igneous minerals by sodic amphiboles and sodic pyroxenes (arfvedsonite, richterite, aegirine and lorenzenite), and decreases gradationally in intensity outwards from the contact (Mader 1986; Pell 1994). Fenitization is therefore interpreted to have occurred during, and is attributable to, intrusion of the Aley carbonatite and explains previous mapping (Mader 1986; Pride 1987a; Pell 1994) of volcano-sedimentary rocks in the lower member of the Kechika as ‘amphibolite’ or ‘syenite’ (Chakhmouradian et al. 2015).

Pre-existing geochronological data for the carbonatite include a single K–Ar date of 339 ± 12 Ma on phlogopite from a sample of an amphibolitized, siltstone xenolith-bearing calcite carbonatite breccia from the western margin of the main carbonatite exposure (Pride et al. 1986). U–Pb dating of zircon separates from the dolomite carbonatite was also attempted by Pride et al. (1986) but failed due to low U–Pb content in sampled zircon. More recently, Chakhmouradian et al. (2015) obtained a high-resolution ion microprobe U–Pb baddeleyite age of 372 ± 8 Ma for the main dolomite phase of the carbonatite.

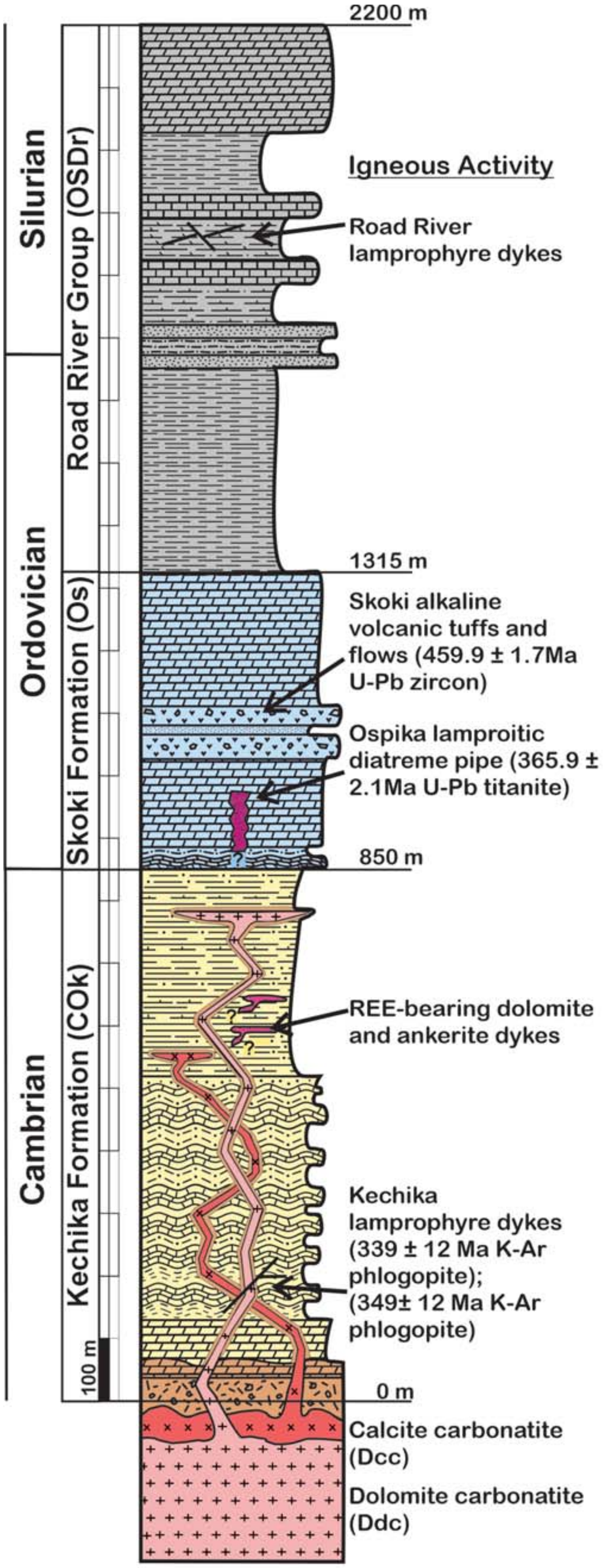

Figure 3. *cont'd* (D) Idealized stratigraphic column of the Aley carbonatite map area (in part, after Pride et al. 1986 and McLeish and Johnston 2019).

Lamprophyre Dykes

Multiple thin (0.5–2.0 m) ultrabasic sills and dykes, including some that are enriched in rare-earth carbonate minerals and which bear distinctive purple fluorite, occur throughout the map area in the host stratigraphy (Fig. 3D) but are most common in the metasomatic fenite aureole peripheral to the carbonatite. Similar dykes intrude the dolomite carbonatite near the core of the western synform (A. Chakhmouradian personal communication 2010). The sills and dykes range in colour from reddish-orange to deep chocolate-brown and are primarily composed of ankerite (Pell 1994). The dykes cut bedding (S_0) and the bedding-parallel cleavage (S_1), and truncate and post-date the fenite metasomatized rocks of the carbonatite contact aureole, indicating that the ultrabasic intrusions post-date D_1 tectonism and carbonatite magmatism. A single K–Ar date of 329 ± 12 Ma was obtained from a sample of biotite lamprophyre talus collected near the carbonatite Kechika Formation contact (Pride 1986).

Ospika Pipe Diatreme

The Ospika pipe is a 50 m-wide ultramafic diatreme pipe intruding the Skoki Formation 500 m west of the western margin of the main carbonatite sill. The pipe weathers a distinct maroon brown, is circular in plan view, and contains both massive and breccia phases. The breccia contains 5–30% subangular to subrounded, randomly oriented xenoliths of Road River Group siltstone that range from sub-centimetre to sub-metre sizes and which are characterized by the bedding-parallel S_1 cleavage. The cleaved wall-rock xenoliths indicate that the diatreme pipe post-dates D_1 deformation that was coeval with carbonatite magmatism. Mineralogically, the pipe is characterized by a phlogopite-dominated, phlogopite–clinopyroxene–olivine macrocryst mineral assemblage hosted in a very fine-grained, hypidiomorphic dolomite–chlorite matrix. Geochemical analyses of the diatreme pipe are consistent with its classification as an aillikite (Pell 1994). A geochronological study of phlogopite separates from the matrix yielded Rb–Sr and K–Ar ages of 334 ± 7 and 323 ± 10 Ma respectively (Pell 1994). These ages are similar to the K–Ar ages reported for the lamprophyre dykes and sills.

METHODS

Igneous units were sampled during mapping for U–Pb zircon, U–Pb titanite, and ^{40}Ar/^{39}Ar phlogopite geochronological analyses at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, Vancouver, Canada. Zircon and titanite were isolated from 5–10 kg samples using standard rock crushing, grinding, and Wilfley table methods, followed by heavy liquid and magnetic separation. Zircon and titanite fractions were handpicked based on differences in crystal quality, size, magnetic susceptibility, and morphology.

Zircon was dated via laser ablation (LA) ICP–MS methods of Tafti et al. (2009) which are summarized in Appendix 1. The ^{206}Pb/^{238}U age is the most precisely determined age for Phanerozoic zircon and is interpreted as the best estimate for the crystallization age of the samples. Assigned ages are based on a weighted average of overlapping, concordant ^{206}Pb/^{238}U ages of individual analyses for each sample. Error ranges for all samples are quoted at the 2σ level. Titanite was dated via chemical abrasion isotope dilution thermal ionization mass spectrometry (CA–ID–TIMS) methods described in Appendix 2. Analytical data for all dated samples discussed in this report are available in Appendix 3.

Samples dated by ^{40}Ar/^{39}Ar methods were prepared by handpicking phlogopite from crushed, ground mineral separates that had been reduced on a Wilfley table. Phlogopite extracts were washed in acetone, dried, wrapped in aluminum foil, and stacked in an irradiation capsule with similar-aged samples and neutron flux monitors. Extracts were then irradiated at the McMaster Nuclear Reactor in Hamilton, Ontario, for 90 MWh, with a neutron flux of approximately 3×10^{16} neutrons/cm^2/s. Analyses (n = 57) of 19 neutron flux monitor positions produced errors of < 0.5% in the J value. The samples were analyzed at the Noble Gas Laboratory at PCIGR. The mineral separates were step-heated at incrementally higher powers in the defocused beam of a 10 W CO_2 laser (New Wave Research MIR10) until fused. The gas evolved from each step was analyzed by a VG5400 mass spectrometer equipped with an ion-counting electron multiplier. All measurements were corrected for total system blank, mass spectrometer sensitivity, mass discrimination, radioactive decay during and subsequent to irradiation, as well as interfering Ar from atmospheric contamination and the irradiation of Ca, Cl and K.

RESULTS

Aley Carbonatite

Zircon fractions obtained from a sample of dolomite carbonatite (MA096) contained near-zero ppm concentrations of radiogenic Pb and therefore could not be used to determine a U–Pb crystallization age of the carbonatite. The sampling locality, an outcrop near the centre of the dolomite core of the intrusion, is characterized by banded to massive fersmite- and pyrite-bearing dolomite-apatite carbonatite typical of the core dolomite carbonatite phase. The zircon grains analyzed were tan-brown to beige, translucent, euhedral, stubby dipyramids and displayed significant resorption and zonation textures in cathodoluminescent light. Whole rock geochemistry of Mader (1986) showed all phases of the carbonatite to have anomalously low U content which suggests that the low Pb content of zircon is due to a lack of U in the parent magma rather than post-crystallization Pb loss.

Skoki (Lady Laurier) Volcanic Unit

Twenty light pink, translucent, elliptical zircon grains were isolated from a sample collected from a 1 m-thick agglomeratic tuff bed, 15 m from the top of the Skoki volcanic member (sample MA062). The sampling locality lies 800 m northwest of the west margin of the carbonatite. Weakly developed growth zonation was observed in all grains under cathodolumiscence. Eighteen of the twenty ^{206}Pb/^{238}U–^{207}Pb/^{235}U data points plot as a tight cluster along the concordia curve at 460 Ma with the remaining four scattered between 450 and 480 Ma (Fig. 4). A weighted average of ^{206}Pb/^{238}U ages for the cluster of 18 accepted analyses is 461.1 ± 1.4 Ma (MSWD=0.37), which is interpreted as the crystallization age of the volcanic unit. This age is in close agreement with a mid-Ordovician age for the Skoki Formation as determined by paleontological investigations (Pyle and Barnes 2003) and is interpreted as the age of volcanism.

Ospika Pipe Diatreme

Titanite grains for single-grain ID–TIMS dating were isolated from a sample of the massive diatreme phase exposed near the core of the pipe (MA045A). The sample was free of visible country rock xenoliths and contained 15% phlogopite megacrysts similar to those dated by Pell (1994). The titanite grains were translucent, pale yellow, and displayed characteris-

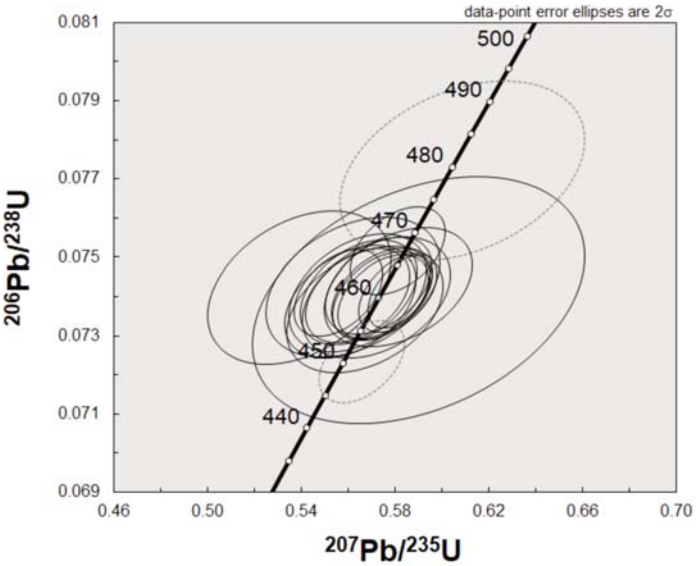

Figure 4. Conventional U–Pb concordia diagram for the Skoki volcanic rock (MA062). Data were used to calculate a weighted average ^{206}Pb/^{238}U age of is 461.1 ± 1.4 Ma (MSWD = 0.37).

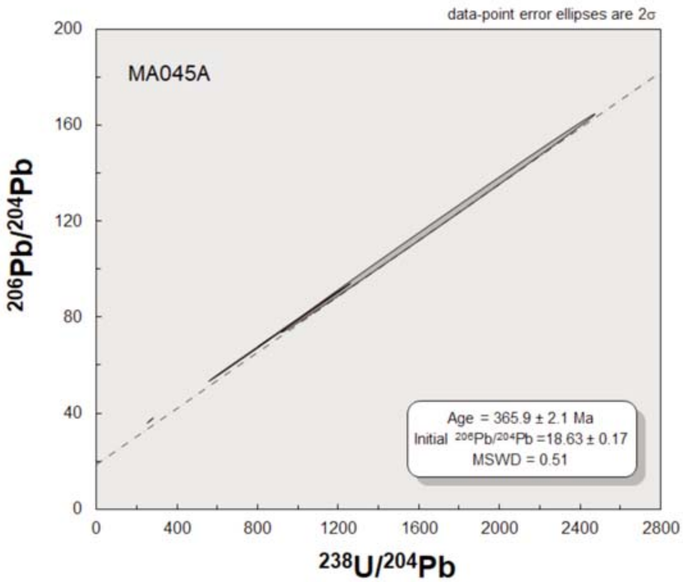

Figure 5. U–Pb analyses of titanite from the Ospika pipe define a four-point isochron of 365.9 ± 2.1 Ma (MSWD = 0.51).

tic wedge-shaped igneous crystal habit. In total, five grains were analyzed and four yielded usable results, which together define a ^{206}Pb/^{238}U isochron age of 365.9 ± 2.1 Ma (MSWD = 0.51; Fig. 5). The titanite age is in reasonable agreement with the ca. 330 Ma K–Ar and Rb–Sr phlogopite dates of Pell (1994), provided the latter two are considered as cooling ages and the titanite age as the igneous crystallization age.

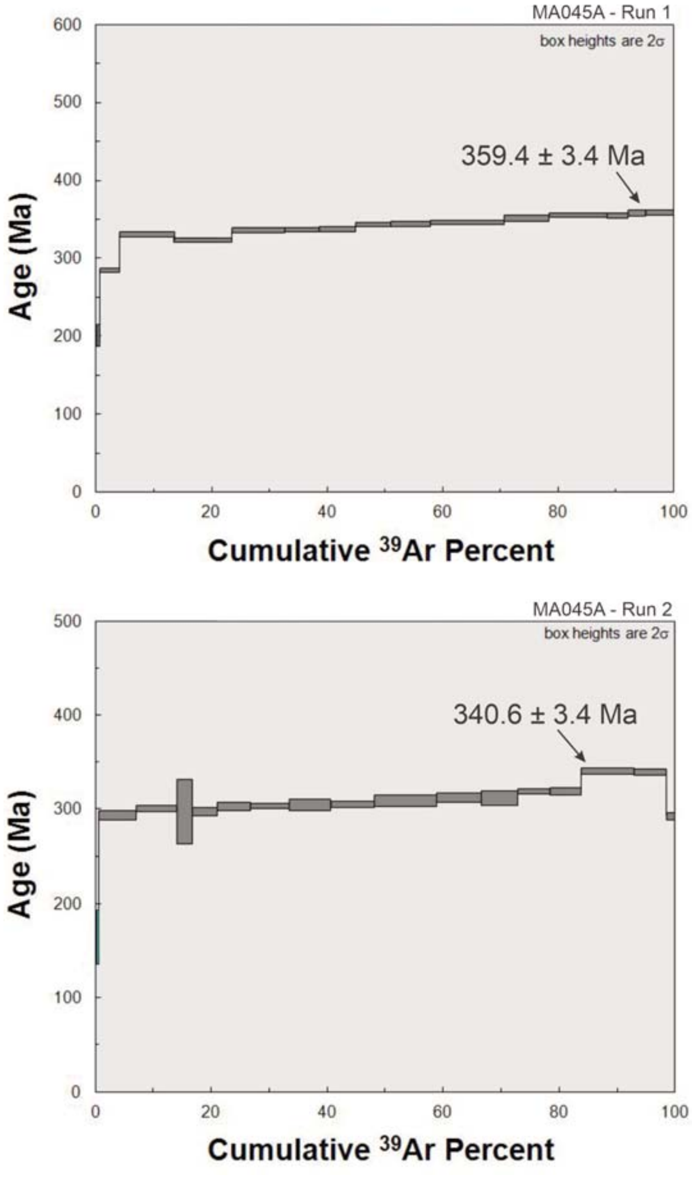

Figure 6. ^{40}Ar/^{39}Ar step heating results for MA045A Run 1 and Run 2.

Phlogopite grains isolated from MA045A were dated with ^{40}Ar/^{39}Ar step-heating techniques to further constrain the cooling history of the Ospika pipe. Two attempts were made to date two separate phlogopite grains; both yielded continuously rising age spectra. We interpret the oldest step in each attempt, 359.4 ± 3.4 Ma and 340.6 ± 3.4 Ma in first and second attempts respectively, as minimum cooling ages for phlogopite (Fig. 6).

Quartzite Clasts from the Volcano-Sedimentary Member of the Kechika Formation

Two cobble-sized quartzite clasts were cut out of two separate 25 kg loose boulder-sized talus (float) samples of fenitized conglomerate (MA076 and MA190) of the lower volcano-sedimentary member of the Kechika Formation and were processed for U–Pb detrital zircon geochronology. The quartzite clasts sampled for dating were nearly pure quartz with accessory concentrations of zircon and opaque minerals. The majority of the zircon grains isolated from the quartzite clasts were too fine-grained to be suitable for LA–ICP–MS analysis; however, 13 and 18 of the near-spherical pink zircon grains were deemed large enough and analyzed from MA076

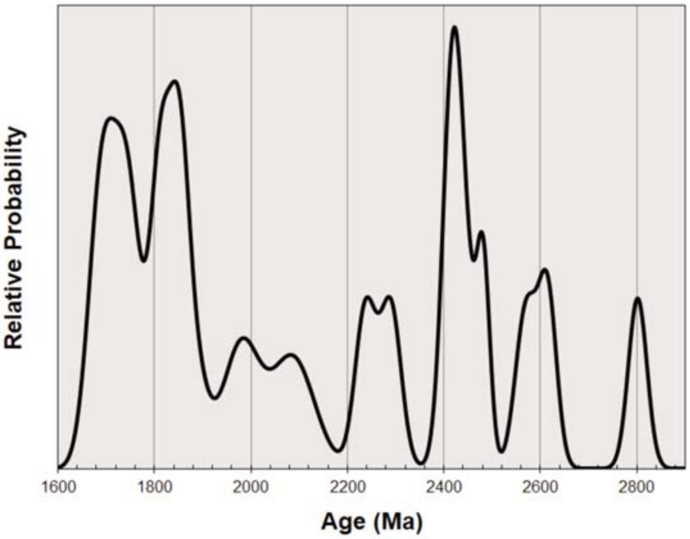

Figure 7. Cumulative probability density plot of $^{206}Pb/^{238}U$ zircon ages analyses (n = 19) that were < 10% discordant for detrital zircon sampled from quartzite clasts of the basal Kechika Formation.

and MA190 respectively. Nearly 40% of the zircons analyzed showed significantly large (> 10%) discordance due to Pb loss and were removed from the age determination results. No statistically significant difference was found between the age populations of the two samples; both age populations ranged from 1.7 to 2.6 Ga with major age probability peaks at 1.8 and 2.4 Ga. A zircon grain from MA076 was the only outlier from the two populations with an age of 2.8 Ga. A MA076–MA190 composite cumulative probability plot was constructed to increase the sample size (Fig. 7) and facilitate comparison with the detrital zircon signature of potential parent units (e.g. Gog Group, as postulated by Mader 1986). The extensive Pb loss displayed by many of the zircon grains is likely due to the extensive metasomatic alteration of the host conglomerate unit during intrusion of the carbonatite.

Lamprophyres

A 0.5 m-wide lamprophyre dyke that intrudes the Skoki Formation, cutting across bedding in a dark grey, fenitized, massive argillaceous dolostone was sampled from the wall rocks of the Ospika pipe for $^{40}Ar/^{39}Ar$ phlogopite analysis. The dyke sampled is characterized by a very fine-grained calcareous, beige to orange 'rock flour' matrix hosting phlogopite megacrysts. Sample MA045D yielded coarse, dark honey brown phlogopite. Two attempts at dating separates both yielded continuously rising age spectra. The oldest step in each attempt, 353.3 ± 3.6 Ma and 352.6 ± 3.5 Ma in the first and second attempts respectively, is interpreted as the minimum age for cooling of the phlogopite (Fig. 8).

DISCUSSION

Globally, deformed alkaline igneous rocks have been associated with and are shown to characterize suture zones of continental collisional orogens (Burke et al. 2003). In the Aley region, detailed structural mapping has shown that the western Foreland Belt of the Canadian Cordillera is characterized by a tectono-magmatic event that was contractional in nature (McLeish and Johnston 2019). Constraining the age of the Aley carbonatite thus offers an opportunity to constrain the age of mid-Paleozoic contractional deformation in the Aley region and, should the age of the Aley carbonatite be correlative with other alkaline–carbonatite complexes in the Foreland Belt, help define a margin-scale deformation event in the Canadian Cordillera.

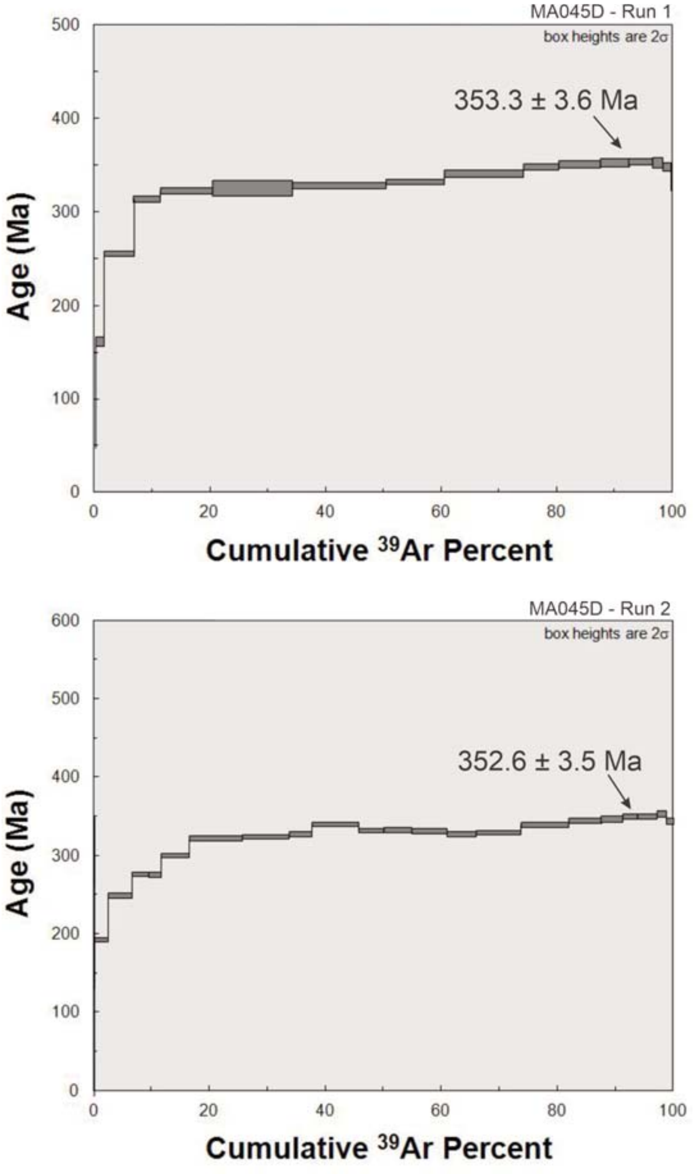

Figure 8. $^{40}Ar/^{39}Ar$ step heating results for MA045D Run 1 and Run 2.

The Aley carbonatite, the lamprophyre dykes and the Ospika pipe share similar 360–340 Ma K–Ar and $^{40}Ar/^{39}Ar$ cooling ages; all are therefore interpreted as having intruded and crystallized prior to 340 Ma. Because carbonatite intrusions are commonly spatially and genetically associated with coeval alkaline intrusive rocks, we argue that the carbonatite, the Ospika pipe and the lamprophyre dykes are attributable to a single magmatic event. The 366 Ma (Late Devonian) U–Pb age for magmatic titanite from the Ospika pipe yields the age of intrusion of the diatreme, and is therefore the minimum possible age of the Aley carbonatite and the D_1 nappe- and cleavage-forming tectonic event. The maximum possible age of the Aley carbonatite is constrained by the Early Devonian age of the Road River Group, the youngest strata intruded by carbonatite dykes and involved in the syn-magmatic D_1 nappe-forming event. Hence carbonatite magmatism, and the coeval D_1 event, is constrained to have occurred between about 400 Ma, the age of the youngest Road River Group intruded by carbonatite dykes, and 366 Ma, the emplacement age of the Ospika pipe, an interval of just over 30 million years. The D_1 tectonic event is therefore constrained to have occurred in the Late Devonian close to, but prior to, 366 Ma.

The 460 Ma U–Pb zircon crystallization age of the Lady Laurier volcanic member of the Skoki Formation is consistent with the Upper Ordovician fossil ages for the Skoki dolostone members. The Lady Laurier volcanic member of the Skoki Formation, despite being characterized by alkaline magmatism (Goodfellow et al. 1995), pre-dated intrusion of the Aley carbonatite by 90 million years and constituted a distinct magmatic event unrelated to the Aley carbonatite. The tectonic controls and implications of this volcanism, which locally significantly disrupted Middle Ordovician passive margin sedimentation, remain poorly understood.

Detrital zircon data from quartzite clasts of the Kechika Formation volcano-sedimentary member indicate that the quartzite has a maximum age of 1680 Ma (late Paleoproterozoic). The age-spectra are similar to those derived from samples of sandstone and quartzite of the Cambrian Atan Group, the northernmost British Columbia Foreland Belt equivalent of the Hamill–Gog Groups (Gehrels and Ross 1998). They differ from those from quartzite of the Ordovician Monkman Formation, which crops out to the immediate south of Aley, in that they do not contain Grenvillian-aged (1.0–1.1 Ga) zircon (Gehrels and Ross 1998).

Paleozoic alkaline volcanic centres and alkaline–carbonatite intrusive complexes are known along the length of the Cordilleran Foreland Belt (Fig. 9). However, whether these alkaline igneous suites and complexes, including the Aley, constitute coeval components of a margin-wide, syn-tectonic alkaline magmatic province has remained unclear due to a paucity of age constraints. Geochronological data exists for only one other carbonatite complex, the Ice River of the southern Rocky Mountains of British Columbia (Fig. 9). Parrish et al. (1987) obtained U–Pb ages of 363.1 ± 2.2 Ma on zircon and 368.8 ± 7.0 Ma on titanite from the Ice River Complex. More recently Tappe and Simonetti (2012) obtained a 361.7 ± 1.0 Ma U–Pb age on perovskite from the Ice River Complex. Available geochronological data are, therefore, consistent with interpretation of the Aley and Ice River complexes having intruded during, and being correlative components of, a major carbonatitic magmatic event that affected the western Foreland Belt. Field relationships constrain the undated alkaline–carbonatite complexes to emplacement in the Late Devonian to Early Mississippian (Pell 1994). Available geological and geochronological constraints are therefore consistent with coeval carbonatite magmatism in the Upper Devonian along the length of the western Foreland Belt of the Canadian Cordillera.

Similarities exist in the stratigraphy that is host to the six alkaline–carbonatite complexes. All intruded deep water shelf–slope carbonate and clastic rocks proximal to and west of the carbonate–shale facies boundary that separates and distinguishes the eastern and western subprovinces of the Foreland Belt. Detailed structural data and mapping at Aley has established that carbonatite magmatism was syn-kinematic with a major collisional tectonic event that gave rise to crustal scale nappes and a related bedding-parallel cleavage. Currie (1975) demonstrated that the Ice River Complex has, like Aley, undergone complex polyphase deformation and that its wall rocks are similarly characterized by an S_1 bedding-parallel cleavage. The fabrics and folds at Ice River have commonly been interpreted as products of Cretaceous Rocky Mountain deformation (Currie 1975) despite an absence of age constraints. Our findings suggest that the bedding-parallel cleavage that characterizes the wall rocks of the Ice River Complex and other carbonatite complexes of the western Foreland Belt, may have resulted from Late Devonian deformation. Demonstrating syn-magmatic tectonism during emplacement of the other foreland carbonatite complexes constitutes a test of our interpretation of the foreland carbonatite complexes as comprising a syn-tectonic alkaline magmatic province.

Structural and stratigraphic data from along the length of the Cordilleran orogen are consistent with a continental scale Late Devonian collisional orogenic event. This event was originally recognized as the Antler Orogen in north-central Nevada (Roberts Mountain area) where large-scale Late Devonian to Early Mississippian folding, nappe formation and thrust sheet emplacement produced a major angular unconformity (Roberts et al. 1958). Johnson (1971) proposed that the Antler orogeny affected the entire North American Cordillera based in part on the recognition by Gabrielse (1963, 1967) of similar contractional structures and unconformities in the Cariboo and Cassiar districts of British Columbia and Yukon. Although there are different models of the Antler orogeny (e.g. Burchfiel and Davis 1972, 1975; Wright and Wyld 2006; Nelson et al. 2006; Colpron and Nelson 2009), the main constraints come from the western US where Antler orogenesis has been attributed to arc–continent collision involving west-dipping subduction of oceanic lithosphere lying west of and continuous with North American continental lithosphere, leading to partial subduction of continental crust beneath a far-traveled arc (Schweickert and Snyder 1981). Obduction of the arc formed the Roberts Mountain allochthon along the Roberts Mountain thrust (Johnson and Pendergast 1981; Speed and Sleep 1982; Dickinson 2004). In Canada, the Antler Orogeny is manifest by mid-Devonian contractional deformation in the Purcell and southern Rocky Mountains (Root 2001); Late Devonian to Early Mississippian erosional unconformities in the Cariboo Mountains and Kootenay Arc (Klepacki 1985; Struik 1986); volcanism and alkaline magmatism along the length of the western Foreland Belt (Goodfellow et al. 1995); and Devono-Mississippian coarse clastic sedimentation in northern British Columbia and Yukon (e.g. Earn Group, Gordey et al. 1987). Paleocurrent indicators suggest that the Earn Group was derived from an uplifted landmass that lay to

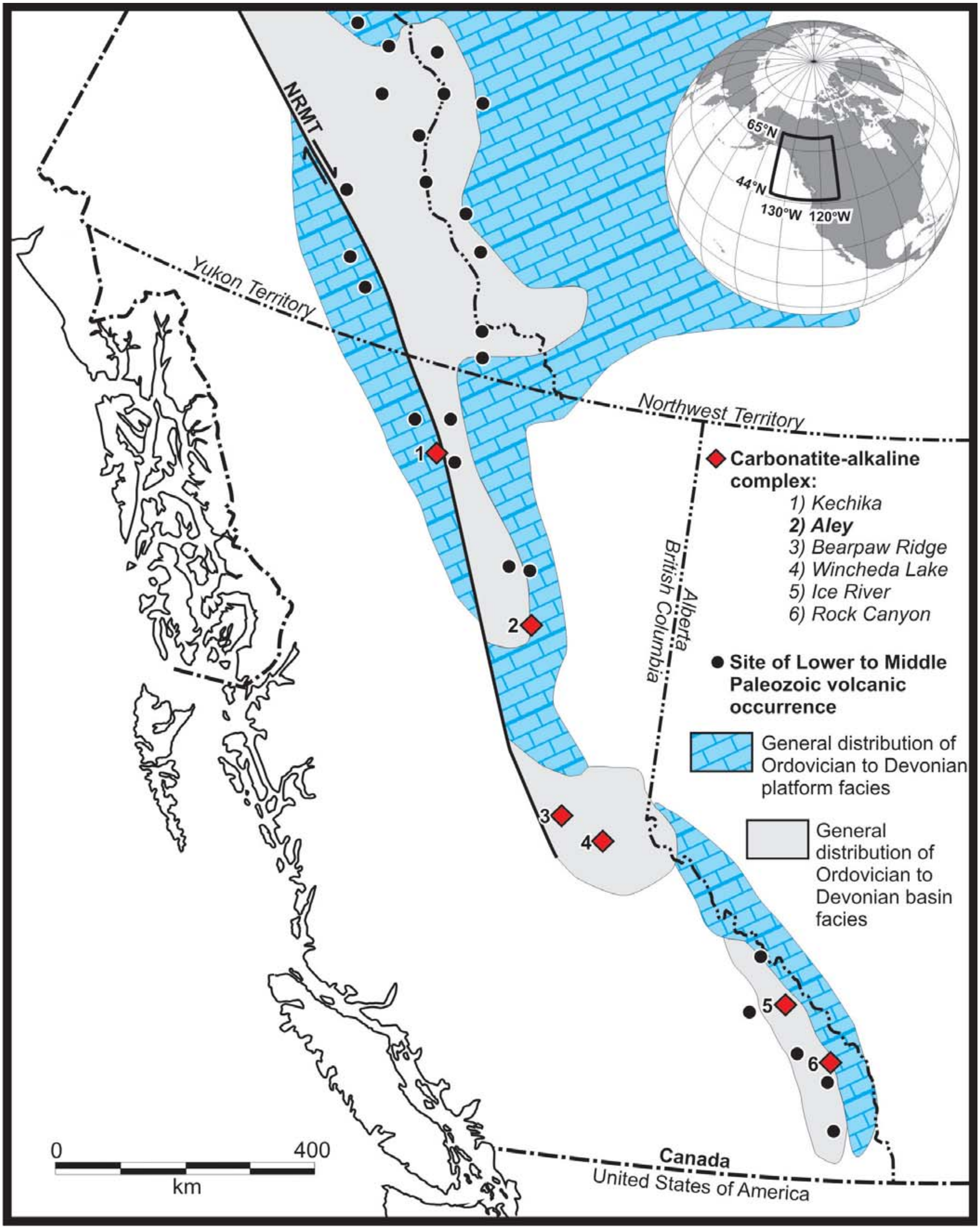

Figure 9. Distribution of early and mid-Paleozoic alkaline volcanic and carbonatite occurrences in the Canadian Cordillera, revised after Goodfellow et al. (1995) with additional data from Hunt (2002).

the west and shed clastic sediment to the east (Gabrielse 1977; Beranek et al. 2016). However, Gordey et al. (1987) suggested that the Earn Group was sourced from uplifted chert and other continental margin rocks to the west, and did not necessarily require an accreting landmass. Beranek et al. (2010) interpreted detrital zircon separated from a sample of the Earn Group as being consistent with such an 'autochthonous' model. However, more recently, Beranak et al. (2016) concluded, based on detrital zircon and Hf isotopic data, that correlative strata in eastern Idaho were derived from a more westerly source, within or west of the intermontane terranes. Finally, Hauck et al. (2017), based on the study of Upper Devonian strata (Sassenach Formation) in the vicinity of Jasper concluded that the accretion of terranes of Caledonian, Baltican or Siberian origin along the Cordilleran and Arctic margins of Laurentia coeval with the Antler orogeny were the source of detrital zircon in the Sassenach Formation.

With respect to the tectonic setting, Gordey et al. (1987) and other workers suggested that extension, not contraction explains Earn Group sedimentation, noting that deposition was concurrent with the eruption of rift-related volcanic rocks, extensional faulting, and the development of exhalative barite and SEDEX and VMS deposits. However, Smith et al. (1993) proposed that Devonian–Mississippian orogenesis characterized the entire Cordilleran margin, that it resulted from continent–arc collision, and that the resulting orogenic welt shed clastic detritus eastward into a foreland basin as exemplified by the westerly-derived Earn Group. In their model, extensional features were explained as products of a migrating orogenic forebulge (Smith et al. 1993). In the Kechika Trough near the Aley area, mid-Devonian syn-sedimentary extensional faulting, formation of exhalative deposits, and rift-related magmatism (Paradis et al. 1998; Piercey et al. 2004) indicate tensile deformation preceded Antler-age contractile deformation and may indicate extension in response to the onset of westward subduction of the continental margin (Schweickert and Snyder 1981). The model by Smith et al. (1993) is consistent with the suggestion by Root (2001) that the basinal western Foreland Belt strata of eastern British Columbia constituted a foreland basin generated by an Antler arc–continent collision in the Middle to Late Devonian (Miall 2019).

The syn-magmatic deformation at Aley Creek appears to have been synchronous with the ca. 370 Ma (Oldow et al. 1989) Antler Orogeny. Observations from the stratigraphic, structural, and magmatic record in our study area indicate that the D_1 event affecting the Aley area is consistent with Antler-style orogenesis: (1) quartzite observed in the Ordovician–Devonian Road River Group is similar to coarse clastic sediment of the Antler-linked Earn Group exposed to the north of the Aley Creek area (Fig. 2); and (2) the syn-magmatic D_1 deformation, including tight folding and nappe formation, is similar to Antler deformation observed in the Kootenay and Cariboo Mountains of southern and central British Columbia.

CONCLUSIONS

Our geochronological data demonstrate that the Aley carbonatite and associated alkaline intrusive units were emplaced at ca. 365 Ma, coeval with the ca. 362 Ma Ice River Complex, and support the interpretation of the carbonatite intrusions of the western Foreland Belt as genetically linked components of an alkaline–carbonatitic magmatic province. Syn-magmatic contractional deformation at Aley suggests that the Foreland Belt carbonatite intrusions are magmatic manifestations of a Late Devonian orogenic event of continental scope. Structural, stratigraphic, and geochronological data from the Aley area indicate that deformation was similar in style to and coeval with structures attributable to the Antler orogeny, supporting the interpretation of the Antler orogen having extended the length of the Cordilleran margin from the southern United States to Alaska. Further structural, stratigraphic, and geochronological investigations of the other five alkaline–carbonatite complexes in the western Foreland Belt of the Canadian Cordillera are required to further test this hypothesis.

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