U-Pb Zircon Geochronology From the Northern Cordillera, Central Yukon, With Implications for Its Tectonic Assembly

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Abstract The tectonic assembly of the Northern Cordillera is currently disputed and directly impacts Paleozoic-to-recent paleogeographic and plate tectonic reconstructions of North America. In this study, we present new U-Pb zircon geochronology from the allochthonous Yukon-Tanana terrane and the parautochthonous Cassiar terrane of the Northern Cordillera from south-central Yukon, Canada. Our data provide new constraints for the assembly of the Northern Cordillera in this region. Metasedimentary samples from the Ingenika Group (Cassiar terrane) and the Snowcap and Finlayson assemblages (Yukon-Tanana terrane) yielded detrital zircon age spectra that are comparable to known northwest Laurentia age spectra. One of our samples from the Snowcap assemblage yields a detrital zircon age spectrum that is anomalous for northwest Laurentia, but comparable to Early Paleozoic strata deposited in the Nevada-Idaho-Utah region. Zircon rim growth and Pb-loss recorded by detrital zircon in the Snowcap assemblage and Ingenika Group samples record metamorphism at 370 ± 4 Ma and between 171 ± 5 and 135 ± 3 Ma. Late Devonian metamorphism and magmatism possibly corresponds to rifting of the Snowcap assemblage from the Laurentian margin. Middle Jurassic-Early Cretaceous metamorphic zircon rim ages from the Cassiar terrane record metamorphism during collisions between the Intermontane superterrane (including the Yukon-Tanana terrane) and Laurentia (Early to Middle Jurassic), and between the Insular superterrane and Laurentia (Middle to Late Jurassic). Our study suggests that collision between the Yukon-Tanana terrane and the Laurentian margin began no earlier than ∼205 Ma.

Plain Language Summary The Northern Cordillera (northwestern North America) represents an amalgamation of continental, volcanic, and oceanic crustal blocks (terranes), which collided with North America (Laurentia) over the last 380 million years. Constraining the timing and sequence of these collisional events is crucial for our understanding of the tectonic and paleogeographic evolution of North America and the natural resources and hazards that it provides. In Yukon, Canada, the most widely accepted models propose that the earliest Cordilleran collisional event occurred between the Yukon-Tanana terrane and Laurentia, ∼270 to 250 million years ago. However, in this study, we present new data which suggest that collision between the Yukon-Tanana terrane and North America took place sometime between 205 and 170 million years ago. Our findings also suggest that the Yukon-Tanana terrane represents a collage of smaller crustal blocks, one of which originated from western North America. Importantly, the present-day structurally overlapping relationships of Cordilleran terranes means that our new interpretation of the Yukon-Tanana-Laurentia collision directly influences the interpretation of all younger and older collisional events in Northern Cordillera. Our study adds to a growing body of evidence that argues that the current and most widely accepted models and terrane definitions for the Northern Cordillera require revision.

1. Introduction The Northern Cordillera of western North America presents a challenging opportunity for elucidating the Paleozoic-Mesozoic paleogeographic evolution of western Laurentia, and advancing our understanding of subduction and continental growth processes in accretionary tectonic environments (e.g., Coney et al., 1980; Monger et al., 1982; Monger & Gibson, 2019; Monger & Price, 1979; Parsons, Zagorevski, et al., 2018; Pavlis et al., 2019; Sigloch & Mihalynuk, 2017; van Staal et al., 2018). Despite its significance, the tectonic evolution of the Northern Cordillera is still contentious due to difficult access, poor bedrock exposure, and the poorly constrained
nature of critical terrane relationships. Hence, a variety of contrasting tectonic models have been developed for the Northern Cordillera, which not only affect our general understanding of North American bedrock geology, but directly impact current models and understanding of Laurentian paleogeography, global tectonic plate networks, and the mantle record of subduction since the late Paleozoic (Clennett et al., 2020; Hildebrand, 2009; Johnston, 2008; Kemp et al., 2021; Monger & Gibson, 2019; Nelson et al., 2013; Parsons, Zagorevski, et al., 2018; Pavlis et al., 2019; Sigloch & Mihalynuk, 2017; van Staal et al., 2018).

Tectonic development of the Northern Cordillera accretionary orogen has dominated the geological evolution of western North America since the Late Devonian (Monger, 1977; Monger et al., 1982; Monger & Gibson, 2019; Monger & Price, 1979; Nelson et al., 2013; Wheeler & McFeely, 1987). The Northern Cordillera developed through multiple episodes of subduction and accretion of exotic and peri-Laurentian continental- and oceanic island-arcs and collapsed ocean basins. Between eastern Alaska and southern British Columbia, the bedrock geology of the Northern Cordillera is characterized by the Intermontane and Insular superterrane, which comprise a collage of allochthonous peri-Laurentian and exotic terranes, respectively (e.g., Monger et al., 1982; Nelson et al., 2013; Wheeler & McFeely, 1987). The tectonic evolution of these terranes is central to the late Paleozoic-Mesozoic paleogeographic evolution of western Laurentia, yet the timing of their accretion to the Laurentian margin remains poorly constrained and highly contested (e.g., Beranek & Mortensen, 2011; Colpron et al., 2015; Hildebrand, 2009; Johnston, 2008; McClelland et al., 1992; Monger et al., 1982; Monger & Gibson, 2019; Nelson et al., 2013; Parsons, Zagorevski, et al., 2018; Pavlis et al., 2019; Sigloch & Mihalynuk, 2017; van Staal et al., 2018).

In this study, we present new zircon U-Pb geochronology and whole-rock geochemistry from the allochthonous, peri-Laurentian Yukon-Tanana terrane (Intermontane super terrane), and the parautochthonous Cassiar terrane (Laurentian margin) in the Dunite Peak region of central Yukon, Canada (Figures 1 and 2). Our results provide (a) new constraints for the detrital zircon provenance of (meta-)sedimentary units of the Yukon-Tanana and Cassiar terranes; and (b) new evidence for a Middle Jurassic-Early Cretaceous metamorphic event recorded by the Yukon-Tanana and Cassiar terranes in south-central Yukon. We interpret this Jurassic-Early Cretaceous metamorphic event as a record of sequential collisions of the Intermontane and Insular superterrane with the west Laurentian margin.

2. The Northern Cordillera of Yukon, British Columbia, and Eastern Alaska

In eastern Alaska, Yukon, western Northwest Territories, and British Columbia, autochthonous and parautochthonous units of the Northern Cordillera comprise a Neoproterozoic to early Paleozoic sedimentary and volcanic-sedimentary stratigraphy deposited along the western passive margin of Laurentia. These stratigraphic units were subsequently deformed and displaced during multiple orogenic events and are now parautochthonous (Hadalari et al., 2012; Lane & Gehrels, 2014; Nelson et al., 2013; Tempelman-Kluit, 1976; Wheeler & McFeely, 1987). Basinal strata in Yukon, north British Columbia, and the Yukon-Tanana Upland in east Alaska were deposited in the Selwyn basin and Richardson and Kechika troughs; these basins were bound by regionally extensive platforms in north and south-central Yukon, western Northwest Territories, and northern British Columbia, including the Ogilvie, Mackenzie, Cassiar-McEvoy, and MacDonald platforms (e.g., Hadlari et al., 2012; Lane & Gehrels, 2014; Nelson et al., 2013). In south-central Yukon, parautochthonous platform strata of the Windermere Supergroup are assigned to the Cassiar terrane, which structurally underlies the Yukon-Tanana terrane (Figures 1 and 2; Colpron, Israel, Murphy, et al., 2016; Wheeler & McFeely, 1987).

In central Yukon and British Columbia, the Intermontane superterrane lies immediately west of, and structurally above the parautochthonous Cassiar terrane (Cook et al., 2004; Evenchick et al., 2007; Nelson et al., 2013). The Intermontane superterrane comprises the island arcs of the Yukon-Tanana, Stikine, and Quesnel terranes and oceanic assemblages of the Slide Mountain and Cache Creek terranes (Figures 1 and 2). The Yukon-Tanana terrane (Figure 1) is an allochthonous terrane of Paleozoic and Mesozoic volcanic arcs built upon a substrate of metamorphosed peri-Laurentian siliciclastic rocks (Colpron, Nelson, & Murphy, 2006; Dusel-Bacon et al., 2006; Mortensen, 1992b; Nelson et al., 2013; Piercy & Colpron, 2009; Tempelman-Kluit, 1979). The siliciclastic basement rocks of the Yukon-Tanana terrane belong to the Snowcap assemblage, which rifted from the Laurentian margin in the Late Devonian-Mississippian, possibly during eastward subduction and back-arc extension of intervening Slide Mountain Ocean (e.g., Colpron et al., 2007; Colpron, Nelson, & Murphy, 2006; Ferri, 1997;
Monger, 1977; Mortensen, 1992a, 1992b; Nelson et al., 2013). Several late Paleozoic arc and rift cycles were built upon Snowcap assemblage basement strata that are not reported from parautochthonous Laurentian units (Colpron, Nelson, & Murphy, 2006; Mortensen, 1992b; Nelson et al., 2013; Tempelman-Kluit, 1979). Distinct phases of collisional deformation and metamorphism are recorded by the Yukon-Tanana terrane during the Late Devonian-Mississippian, Middle Permian to Middle Triassic, latest Triassic to Early Jurassic, Late Jurassic to Early Cretaceous, and Late Cretaceous (Berman et al., 2007; Creaser et al., 1997; Devine et al., 2006; Erdmer et al., 1998; Gilotti et al., 2017; Kellett et al., 2018; Mortensen, 1992b; Ryan et al., 2021; Staples et al., 2016; Vice et al., 2020). Exposures of parautochthonous Laurentian units west of the Yukon-Tanana terrane and geophysical subsurface observations from Yukon and British Columbia, suggest that the Yukon-Tanana terrane forms a klippe overlying parautochthonous Laurentian units (Calvert et al., 2017; Colpron, Israel, Murphy, et al., 2016; Cook et al., 2004).

The timing of accretion of the Yukon-Tanana terrane to Laurentia is poorly constrained; previous studies have proposed accretion during the Middle to Late Permian (Beranek & Mortensen, 2011; Colpron, Mortensen, et al., 2006; Mortensen, 1992b; Nelson et al., 2013), the latest Triassic-Early Jurassic (Ewencich et al., 2007; Gordey, 2002, 2013; Hansen & Dusel-Bacon, 1998; Nixon et al., 2020; Parsons, Zagorevski, et al., 2018; Plint & Gordon, 1997; Stevens et al., 1996), or the Early Cretaceous (Hildebrand, 2009; Johnston, 2008). The identification of an Early to Middle Permian intra-oceanic arc within the Slide Mountain terrane led Parsons, Zagorevski, et al. (2018) and van Staal et al. (2018) to revise the history of terrane accretion in Yukon. Those authors proposed that the Middle Permian high-pressure collisional event recorded in the Yukon-Tanana terrane (the Klondike orogeny of Beranek & Mortensen, 2011) corresponded to its collision with the Dunite Peak intra-oceanic arc.
Figure 2. Geological map of the Dunite Peak region in south-central Yukon (after Parsons, Zagorevski, et al., 2018). Yellow dots show locations of samples analyzed in this study. Blue dots display previously published U-Pb zircon (with “z” notation) and monazite (with “m” notation) geochronology from de Keijzer et al. (1999), Gallagher (1999), and Parsons, Zagorevski, et al. (2018). Map location with respect to Yukon is shown in Figure 1.
located between the Yukon-Tanana terrane and Laurentia. Consequently, Parsons, Zagorevski, et al. (2018) argued that accretion of the composite Yukon-Tanana terrane-plus-Dunite Peak arc to Laurentia occurred during latest Triassic-Early Jurassic deformation and metamorphism, which is observed in both Yukon-Tanana terrane and Laurentian margin units (e.g., Dusel-Bacon et al., 2002; Evenchick et al., 2007; Gordey, 2002, 2013; Hansen & Dusel-Bacon, 1998; Nixon et al., 2020; Plint & Gordon, 1997; Stevens et al., 1996; Tempelman-Kluit, 1979). Furthermore, complexity and uncertainty is added to the tectonic evolution of this region by the poorly constrained kinematic history of the allochthonous Quesnel, Stikine, and Cache Creek terranes. These terranes, which form parts of the larger Intermontane superterrane, collided with each other and the Laurentian margin by the Middle Jurassic (e.g., Colpron et al., 2015; Logan & Mihalynuk, 2014; Mihalynuk et al., 1994, 2004). The Quesnel and Stikine terranes display potential stratigraphic ties with rocks from the Yukon-Tanana terrane (e.g., Colpron et al., 2007; Currie & Parrish, 1997; Mortensen, 1992b), although recent work suggests the Stikine terrane may have originated from the Arctic region of the Caledonides (George et al., 2021).

West of the Intermontane superterrane, the Insular superterrane (Figure 1) comprises allochthonous terranes with Baltic affinities, including the Alexander, Peninsula, and Wrangellia terranes (Beranek et al., 2013; Colpron & Nelson, 2009; Nelson et al., 2013; White et al., 2016). These amalgamated with each other, outboard of Laurentia, prior to the Permian (Beranek et al., 2014), and then accreted to the Northern Cordillera during either the Early to Middle Jurassic (Gehrels et al., 2009; McClelland et al., 1992; McClelland & Gehrels, 1990; Monger & Gibson, 2019; Saleeby, 2000; Yokelson et al., 2015), or the Late Jurassic to Early Cretaceous (Clennett et al., 2020; Sigloch & Mihalynuk, 2017). We interpret the results of our study in the context of the above listed collisional events, with the aim of advancing our understanding of the tectonic evolution of the Northern Cordillera in this region.

3. Study Area: Dunite Peak, Big Salmon Range, Yukon

The Dunite Peak region is located in the Big Salmon Range of central Yukon. We targeted this region because (a) it contains exposures of the Yukon-Tanana, Slide Mountain, and Cassiar terranes in close proximity; and (b) because the level of outcrop exposure and topographic relief provides a rare opportunity to observe large structural sections through these terranes and the structural and stratigraphic relationships within and between them (Figure 2; de Keijzer et al., 1999; Parsons et al., 2017, Parsons, Zagorevski, et al., 2018; Westberg, 2009; Westberg et al., 2009). From structural top to bottom, Dunite Peak is capped by the Dunite Peak ophiolite, which consists of variably serpentinized dunite, harzburgite and minor lherzolite structurally overlying a strongly sheared sequence of metamorphosed, mafic to intermediate plutonic, volcanic, and volcaniclastic rocks (Parsons et al., 2017, Parsons, Zagorevski, et al., 2018). Whole-rock geochemical and Sm-Nd isotopic compositions of these rocks have juvenile, island arc tholeiite, and back-arc basin basalt signatures indicative of an intra-oceanic arc to back-arc setting (Parsons, Zagorevski, et al., 2018). U-Pb zircon geochronology yielded ages of 265 ± 4 Ma from a gabbro sample (Parsons, Zagorevski, et al., 2018) and 267 ± 10 Ma from a plagiogranite sample (de Keijzer et al., 2000; Figure 2), which are interpreted to reflect the timing of Dunite Peak arc magmatism.

The Dunite Peak ophiolite is structurally underlain by a sequence of variably deformed and mylonitized carbonaceous quartzite (metasedimentary protolith), marble, and shale, and rare pillow basalt and volcaniclastic rocks (Figure 2). These units are assigned to the Devonian to Pennsylvanian Finlayson assemblage of the Yukon-Tanana terrane (Parsons et al., 2017, Parsons, Zagorevski, et al., 2018). The Finlayson assemblage records continental and island arc magmatism and sedimentation after the Late Devonian rifting of Yukon-Tanana basement units from Laurentia (Colpron et al., 2007; Mortensen, 1992b; Tempelman-Kluit, 1976). The volcano-sedimentary rocks of the Finlayson assemblage are structurally underlain by marble with subordinate layers of garnet-amphibole calcareous schist and garnet-kyanite pelitic schist (Parsons et al., 2017; Parsons, Zagorevski, et al., 2018). These high-grade metasedimentary units are assigned to the pre-Late Devonian Snowcap assemblage of the Yukon-Tanana terrane (Figure 2), which comprises metamorphosed siliciclastic rocks that were deposited on the Laurentian margin prior to Late Devonian rifting from the margin (Colpron et al., 2007; Nelson et al., 2013). Approximately 15 km northwest of Dunite Peak, the Snowcap assemblage is intruded by augen orthogneiss of the Mississippian Simpson Range plutonic suite with a U-Pb zircon age of 331.5 ± 2 Ma (Figure 2; Colpron, Israel, & Friend, 2016; de Keijzer et al., 2000). Correlative Mississippian intrusions are also reported intruding the Snowcap Assemblage approximately 20 km south of Dunite Peak (Westberg, 2009; Westberg et al., 2009).
Cassiar terrane sedimentary rocks are exposed ~10 km east of Dunite Peak. They comprise marble, shale and quartzite with subordinate foliation-parallel meta-igneous layers (Figure 2). The structural boundary between the Yukon-Tanana and Cassiar terranes is not exposed in the Dunite Peak region, but has been inferred by previous studies to strike north-south along the base of the intervening valley between mapped outcrops (Figure 2; Colpron, Israel, Murphy, et al., 2016). Elsewhere, this boundary is mapped as the Inconnu thrust (Murphy et al., 2006) and the Tummel fault zone (Colpron et al., 2005). Available constraints suggest that this terrane boundary records ductile deformation sometime between the Middle Triassic to Early Jurassic and brittle deformation after the Jurassic (Colpron et al., 2005; Murphy et al., 2006).

Cretaceous granites intrude both the Yukon-Tanana and Cassiar terranes (Colpron, Israel, & Friend, 2016). Local to the Dunite Peak region (Figure 2), the Yukon-Tanana terrane is intruded by the Early Cretaceous d’Abbadie granite (109 ± 3 Ma; part of the Cassiar plutonic suite) and Dycker Creek Stock (112 ± 1 Ma; part of the Cassiar plutonic suite), and the Late Cretaceous Last Peak granite (96 ± 1 Ma; part of the Seagull plutonic suite; Colpron, Israel, & Friend, 2016; de Keijzer et al., 2000; Gallagher, 1999; Westberg et al., 2009). The Last Peak granite is deformed by the north-south striking d’Abbadie fault system (Figure 2), which displays ~4 km right-lateral displacement, and is interpreted to have formed initially as a normal fault (Colpron et al., 2017; de Keijzer et al., 1999).

4. Methods: U-Pb Zircon Geochronology and Whole-Rock Geochemistry

Zircon U-Pb isotopic analysis was conducted on seven samples from the Dunite Peak area (Figure 2). Three samples were collected from outcrops mapped as Snowcap assemblage (samples 17RAY-AP012B1 and 16RAY-AP077B1) and Finlayson assemblage (sample 17RAY-AP017A1) strata of the Yukon-Tanana terrane (Figure 2). The remaining four samples were collected from outcrops mapped as Ingenika Group strata (samples 17RAY-AP014A2, 17RAY-AP015A1, 17RAY-AP016A2, and 17RAY-AP016C1), which belong to the Cassiar terrane (Figure 2). Sample locations are listed in Table 1.

Meta-igneous samples 17RAY-AP015A1 and 17RAY-AP016C1 were selected for secondary ion microprobe spectrometry (SIMS; Figures 3a and 3b). Meta-sedimentary samples 16RAY-AP077B1, 17RAY-AP012B1, 17RAY-AP014A2, 17RAY-AP016A2, and 17RAY-AP017A1 were selected for laser ablation induced coupled plasma mass spectroscopy (LA-ICPMS; Figures 4–6). Subsidiary sets of zircon from samples 17RAY-AP012B1 and 17RAY-AP014A2 were also analyzed via SIMS. SIMS and LA-ICPMS analyses were conducted at the Stanford-USGS Microanalytical Center at Stanford University (Stanford, CA, USA) and the Arizona LaserChron Laboratory at the University of Arizona (Tucson, AZ, USA), respectively. Whole-rock major and trace element geochemical analyses (Figures 3c–3h and 7) were conducted by Activation Laboratories Ltd. (Ancaster, ON, USA; 4Lithoresearch package: lithium metaborate-tetraborate fusion, ICP, and ICP-MS).

SIMS analyses of meta-igneous samples (17RAY-AP015A1 and 17RAY-AP016C1) and meta-sedimentary samples (17RAY-AP012B1 and 17RAY-AP014A2) are presented in Sections 4.1 and 4.2, respectively. SIMS ages for meta-igneous samples (Figures 3a and 3b) are based on Concordia ages (Ludwig, 1998) calculated after common Pb correction by the 206Pb/207Pb-method (Data Set S1). For SIMS analyses of meta-sedimentary samples, selection of preferred age is based a 206Pb/238U cut-off date of 1,200 Ma. For data with 206Pb/235U dates <1,200 Ma, 206Pb/235U dates, corrected for common Pb by the 207Pb-method, are preferred. For data with 206Pb/235U dates >1,200 Ma, 207Pb/206Pb dates, corrected for common Pb by the 207Pb-method, are preferred. CL-images of zircon analyzed via SIMS are presented in Supporting Information S1 (Figure S1).

LA-ICPMS analyses are presented in Section 4.2. Dates that are >10% discordant, >5% reversely discordant, with discordance based on ([206Pb/238U date/206Pb/207Pb date) – (analytical error propagated at 2σ level)], following equations in Gibson et al. (2021), or have uncertainties (2σ, analytical error) of >10% in the 206Pb/238U date, >10% in the 207Pb/206Pb date for >700 Ma and >25% in the 207Pb/206Pb date for <700 Ma are not included in our discussion of provenance but used to evaluate the effects and timing of post-depositional metamorphism (Figures 4–6). 208Pb/238U dates are preferred for dates less than 1,200 Ma, whereas 207Pb/206Pb dates are preferred for dates older than 1,200 Ma. In cases where the 206Pb/238U and 207Pb/206Pb dates straddle 1,200 Ma, the date with lower uncertainty is used. Results from samples 17RAY-AP014A2 and 17RAY-AP012B1 also include data collected from subsidiary sets of zircon via SIMS using analytical (random, measurement, and internal) and systematic (external) error (2σ) added in quadrature.
Table 1
Summary of Geochronology Results

| Sample   | Location          | Lithology/ tectonostratigraphic unit/terrane                                                                 | Condondant dates/total number of dates | Zircon age spread                         | Youngest detrital zircon | Metamorphic ages | Discordant zircon intercept | Inherited zircon | Magmatic age (Ma), (dates used/total number of dates) |
|----------|-------------------|-------------------------------------------------------------------------------------------------------------|----------------------------------------|------------------------------------------|-------------------------|-----------------|---------------------------|-----------------|------------------------------------------------------|
| 17RAY-AP015A1 | 61.66992865N, 133.69437437W | Undeformed biotite-monzogranite/Cassiar Magmatic Suite/ Cassiar terrane                                        | 12/12                                  | 1110 ± 20, 137 ± 2, and 123 ± 4–110 ± 3 Ma | –                       | –               | –                         | 137 ± 2 Ma, 1110 ± 20 Ma | 116 ± 2 Ma, (10/12) |
| 17RAY-AP016C1 | 61.59245283N, 133.76717491W | Foliated, metamorphosed monzogranite/Scagull group OR Earn Group/Cassiar terrane                               | 11/11                                  | 392 ± 5–356 ± 7 and 267 ± 2 Ma             | –                       | –               | –                         | –               | 372 ± 5 Ma, (10/11) |
| 17RAY-AP014A2 | 61.66838382N, 133.69054037W | Biotite-sillimanite-schist/ Ingenik Group/ Cassiar terrane                                                  | 136/321                                | 1,140, 1,810, 568 ± 10 Ma, 2,090, and 2,670 Ma | 134 ± 5 Ma (single rim analysis), 370 ± 4 Ma (Concordia age, n = 4) | –               | –                         | Late Devonian to Early Cretaceous—poorly defined | –               | – |
| 17RAY-AP016A2 | 61.59245283N, 133.76717491W | Marble/Ingenik Group/ Cassiar terrane                                                                       | 135/313                                | 1,430, 1,770, 616 ± 21 Ma, 1,850, 2,570, and 2,660 Ma | 171 ± 5 Ma to 135 ± 3 Ma (single rim analysis), 166 ± 2 Ma (Concordia age, n = 5), 139 ± 2 Ma (Concordia age, n = 4) | –               | –                         | Jurassic to Early Cretaceous | –               | – |
| 16RAY-AP077B1 | 61.55787034N, 133.88513442W | Garnet-kyanite-biotite-schist/Snowcap assemblage/Yukon-Tanana terrane                                        | 139/348                                | 710, 1,380, 1,760, and 2,680 Ma            | 530 ± 16 Ma              | Metamorphic rims identified—no robust ages measured | ~190 to 130 Ma | – | – |
| 17RAY-AP012B1 | 61.66532651N, 133.83913335W | Chlorite-mica-schist/ Snowcap assemblage/Yukon-Tanana terrane                                                | 154/309                                | 1,150, 1,870, 922 ± 27 Ma, 2,100, and 2,730 Ma | Metamorphic rims identified—no robust ages measured | Paleozoic to Mesozoic—poorly defined | – | – |
| 17RAY-AP017A1 | 61.59250735N, 133.89874506W | White quartzite/Finlayson assemblage/Yukon-Tanana terrane                                                   | 270/314                                | 1,020, 1,830, 988 ± 18 Ma, 1,910, 2,070, and 2,640 Ma | None                     | Metamorphic rims identified—no robust ages measured | Paleozoic to Neoproterozoic | – | – |

Note: Complete dataset is presented in Data Set S1.
Zircon with complex histories provide unique challenges for data interpretation. Outliers from a single population may be the result of mixing of different intra-grain age domains during analysis, Pb-loss, high common Pb due to metamictization or alteration, or analysis of inclusions (e.g., Gehrels, 2014). The potential for mixed domains and Pb loss in each measured volume is greatly increased in grains that have experienced either pre-depositional metamorphism (e.g., McClelland et al., 2016) or post-depositional metamorphism (e.g., Gilotti et al., 2017). A high degree of discordance in a detrital zircon population is a defining characteristic of metasedimentary rocks, which results in an increased probability of altering the observed age distribution. Comparison of plots generated...
Figure 4. U-Pb isotope concordia plots for detrital zircon samples (a) and (b) 17RAY-AP016A2, (c) and (d) 17RAY-AP014A2, (e) and (f) 16RAY-AP0771B1, (g) 17RAY-AP012B1, and (h) 17RAY-AP017A1. Gray ellipses define dates which do not pass our criteria for concordance and uncertainty. Error ellipses plotted as 1σ analytical error.
for each sample using concordant data only versus the discordance filters cited above are provided in Supporting Information S1 (Figure S2) to evaluate the potential impact of the Pb loss. Although the peaks produced by the “concordant-only” data (light blue line) have lower amplitudes due to the lower number of dates in the concordant-only data, the ages and shapes of the dominant age peaks remain relatively unchanged with respect to the “discordance-filtered” data (dark blue line). Discordance-filtered age peaks presented in Figure 6 can therefore be used to make robust inferences of sediment provenance.

Figure 5. Evidence for metamorphic zircon growth. (a)–(c) False color cathodoluminescence images of detrital zircon from samples (a) 16RAY-APO77B1, (b) 17RAY-AP016A2, and (c) 17RAY-AP017A1. Numbers correspond to individual spot analyses presented in Data Set S1. (d) and (e) Results of analysis of CL-bright domains interpreted as metamorphic zircon growth in samples (d) 17RAYAP014A2 and (e) 17RAY-AP016A2. Error ellipses plotted as 2σ analytical error. Black error ellipses are used to calculate Concordia ages (bold ellipses) are plotted with 2σ systematic error. MSWD cited for concordance and equivalence.
Figure 6. Probability density distribution and histogram plots of detrital zircon U-Pb ages from samples (a) 17RAY-AP016A2, (b) 17RAY-AP014A2, (c) 16RAY-AP077B1, (d) 17RAY-AP012B1, and (e) 17RAY-AP017A, plotted alongside zircon reference spectra for (f) and (g) North Laurentia Type 1 and Type 2 (Hadlari et al., 2012), (h) West Laurentia Facies B (Matthews et al., 2018), and (i) West Laurentia Belt-Purcell Supergroup (dark green line; Doughty & Chamberlain, 1996; Doughty et al., 1998; Evans et al., 2000; Jones et al., 2015; Lewis et al., 2007; Link et al., 2016; Ross & Villeneuve, 2003; Sears et al., 1998; Stewart et al., 2010) and Southwest Laurentia Yavapai-Mazatzal Province (light green fill; Amato et al., 2008; Daniel et al., 2013; Doe et al., 2012, 2013; Jessup et al., 2005; Jones & Connelly, 2006; Jones et al., 2009, 2011, 2015; Jones & Thrane, 2012). Histogram bin width is 75 Myr. (j) Cumulative frequency plot for all samples, and reference spectra. Colored vertical bars behind histogram and probability distribution plots define distinct zircon age sources based on Ross and Villeneuve (2003), Amato et al. (2009), Gehrels et al. (2011), Hadlari et al. (2012), Nelson et al. (2013), Malone et al. (2014), Cowood and Pisarevsky (2017), Linde et al. (2017), Malone et al. (2017), Estrada et al. (2018), and Dewing et al. (2019). Vertical blue lines define peaks Neooproterozoic zircon production on Laurentia from the Gunbarrel magmatic suite (~780 Ma) the Franklin, Tatonduk, Eagle Creek, and Mount Harper magmatic suites (~725 to 713 Ma), the Gataga volcanics (~569 to 684 Ma), the Pool Creek suite (~650 to 640 Ma), and the Hamil volcanics (~570 Ma) in Alaska and western and northern Canada, and equivalent igneous suites from Idaho, Utah, and Nevada (~730 to 650 Ma). Plotted using spreadsheets provided by the Arizona Laserchron Center (www.laserchron.org). Stratigraphic era abbreviations. Cal., Calymnian; C., Cenozoic; Cr., Cryogenian; Ect., Ectasian; E., Ediacaran; Mes., Mesozoic; Or., Orosirian; Pale., Paleozoic; Rhy., Rhyacian; Sid., Siderian; Ste., Steenian; Sta., Statherian; Ton., Tonian.
Data that does not pass the discordance filter criteria is not used in our evaluation of provenance but is incorporated into our discussion and interpretation of the timing of metamorphism. In addition, textural observations and compositional data are used to guide our analysis and interpretation of metamorphic rims or domains further. Dates interpreted to reflect zircon growth during metamorphism are evaluated and grouped on the basis of concordance and the degree of overlap exhibited by the results. Concordia ages (Ludwig, 1998) are calculated...
from metamorphic rim data using IsoplottR (Vermeshch, 2018). Outlier rim dates with high common Pb, high uncertainty, or discordance are also considered (but not included in Concordia ages), where metamorphism may be responsible for those outliers.

Figures 3a, 3b, 4, 5, and 6 were plotted using IsoplottR 4.1 (Ludwig, 2012), IsoplottR (Vermeshch, 2018), and AgeCalcML 1.42 (Sundell et al., 2021). Results and key interpretations are summarized in Table 1. CL-images of zircon are presented in Figure 5 and Supporting Information S1 (Figure S1). Analytical procedures for SIMS, LA-ICPMS, and whole-rock geochemical analyses are described in Supporting Information S1. The complete SIMS, LA-ICPMS, and whole-rock geochemical datasets are presented in Data Set S1.

4.1. Results: SIMS

4.1.1. 17RAY-AP015A1

Sample 17RAY-AP015A1 is an undeformed biotite-monzogranite (Figure 3a) collected from a small outcrop (~25 m × 25 m area) located ~50 m downslope of sample 17RAY-AP014A2 (Cassiar terrane, Figure 2). It is enriched in light rare earth elements (LREEs) and light HFSEs by an order of magnitude relative to heavy rare earth element (HREEs) and heavy HFSEs (Figure 3c). HREE and heavy HFSE concentrations are slightly elevated with respect to N-MORB concentrations (Figure 3c). Relative concentrations of FeO, MgO, and alkaline content, and depletion in Eu, Ti, V, and Sc are indicative of a peraluminous, calc-alkaline, and S-type granite (Figures 3d–3h).

Sample 17RAY-AP015A1 yielded subhedral to euhedral zircon texturally ranging from well-developed oscillatory zoning to low-U core and high-U rim textures. Spot analyses were conducted on 12 zircon grains. A single measurement of a CL-bright, low U (66 ppm) core (spot 12.1) gave a 206Pb/238U date of 1,110 ± 20 Ma (1σ analytical error) that is interpreted to reflect the age of an inherited component in the sample. The remaining analyses targeted CL-dark domains and gave 206Pb/238U dates of 137 ± 2–110 ± 3 Ma (1σ analytical error). The oldest date in this range (spot 12.1, 137 ± 2 Ma) was from measurement of an inner rim that overgrows a CL-bright core and surrounded by a CL-dark rim. This date is a clear outlier from the younger population and is interpreted as a mixed age or older metamorphic rim on a xenocryst based on the lower U (239 ppm), low Th/U (0.004), and lighter CL response. The remaining dates (123 ± 4–110 ± 3 Ma), with higher U (786–2,562 ppm) and lower Th/U (0.01–0.10) are interpreted to record igneous zircon growth and define a Concordia age of 116 ± 2 Ma (2σ systematic error; MSWD = 1.9 for concordance and equivalence; n = 10) which we interpret as the magmatic crystallization age of the undeformed biotite-monzogranite sample 17RAY-AP015A1 (Figure 3a).

4.1.2. 17RAY-AP016C1

Sample 17RAY-AP016C1 is a foliated, feldspar augen-muscovite-biotite-schist (Figure 3b) collected from a ~5 m thick layer within a foliated marble (sample 17RAY-AP016A2, see below). At this outcrop (Figure 2), compositional layering and foliation are parallel. The outcrop is mapped as part of the Ingenika Group (Cassiar terrane, Figure 2; Colpron, Israel, Murphy, et al., 2016). The sample of augen schist is enriched in light rare earth elements (LREEs) and light HFSEs by an order of magnitude relative to heavy rare earth element (HREEs) and heavy HFSEs (Figure 3c). HREE and heavy HFSE concentrations are slightly elevated with respect to N-MORB concentrations (Figure 3c). Based on sample lithology and whole rock geochemistry, combined with its unimodal population of zircon dates, and presence of recrystallized feldspar augen, we interpret sample 17RAY-AP016C1 as a metamorphosed monzogranite. Relative concentrations of FeO, MgO, and alkaline content, and depletion in Eu, Ti, V, and Sc are indicative of a peraluminous, calc-alkaline, and S-type granite (Figures 3d–3h).

Sample 17RAY-AP016C1 yielded subhedral to euhedral zircon with well-developed oscillatory zoning in entire grains or in rims that overgrow cores. Spot analyses targeting the oscillatory zoned domains were conducted on 11 zircon grains. Ten measurements produce a cluster of 206Pb/238U dates ranging between 392 ± 5 and 356 ± 7 Ma (1σ analytical error; Figure 3b). These 10 measurements define a Concordia age of 372 ± 5 Ma (2σ systematic error; MSWD = 2.8 for concordance and equivalence; n = 10) and have U concentrations and Th/U ratios of 144–772 ppm and 0.06–0.40, respectively. Spot 3.1 gave a young 206Pb/238U date (267 ± 2 Ma; 1σ analytical error) that combined with high U (1,830 ppm) and significant common Pb correction suggests the analysis is an outlier from the main population due to real age variation, Pb-loss, or presence of inclusions. We
interpret the Concordia age as the magmatic crystallization age, which provides a minimum depositional age for the surrounding marble layers (sample 17RAY-AP016A2).

4.2. Results: LA-ICPMS

4.2.1. 16RAY-AP077B1

Sample 16RAY-AP077B1 (Figures 4e and 4f) is a strongly foliated, garnet-biotite-schist with rare kyanite grains, collected from a 0.5 m thick bed within marble; this outcrop is currently assigned to the Snowcap assemblage of the Yukon-Tanana terrane (Figure 2). The zircon population recovered from this sample includes subhedral, equant to elongate, and subrounded grain fragments (Figure 5a). Most grains exhibit clear core rim relationships with oscillatory-zoned cores overgrown by 1–20 μm thick CL-bright rims (Figure 5a). Spot analyses were conducted on 348 zircon grains: 310 analyses targeted homogeneous core domains and 38 analyses attempted to target CL-bright rim domains. A total of 208 measurements (60%) do not pass the discordance and uncertainty filters for detrital ages (Figures 4e and 4f). The remaining 139 grains yielded interpreted detrital zircon ages (Figures 4e, 4f, and 6c) ranging between the latest Mesoarchean to early Paleoproterozoic, middle Paleoproterozoic to late Mesoproterozoic, and early to late Neoproterozoic. Neoproterozoic and Archean to Siderian zircons have U concentration and Th/U ratios of 51–652 ppm and 0.06–1.6, respectively, whereas late Paleoproterozoic to Mesoproterozoic zircons have U concentration and Th/U ratios of 39–919 ppm and 0.05–1.1, respectively. The probability distribution of zircon ages (Figure 6c) shows clusters of Neoarchean, Orosirian to Statherian, Calymmian to Statherian, and late Tonian to Cryogenian ages, with age-peaks of 2,680 Ma (n = 5), 1,852 Ma (n = 8), 1,751 Ma (n = 37), 1,442 Ma (n = 8), 1,390 Ma (n = 11), and 713 Ma (n = 4). The youngest concordant single grain zircon age of 530 ± 16 Ma (2σ systematic error) was obtained from a rim analysis that may record the detrital igneous or metamorphic protolith or a mix of metamorphic rim and detrital protolith. The youngest accepted core analysis gave an age of 600 ± 35 Ma (2σ systematic error). Recognizing the result may reflect some Pb loss or metamorphic overprint, 530 ± 16 Ma is interpreted as a maximum depositional age for this sample.

Results from analyses specifically targeting rim material failed to isolate a robust concordant population to define rim ages. The five youngest 206Pb/238U dates range from 95 to 192 Ma but have high common Pb and high uncertainty in the measured 207Pb/206Pb ratios. They do, however, record lower Th/U (0.01–0.06 and 0.24) which suggests a metamorphic origin for the CL-bright rims. Core-rim pairs noted in Supplementary table DR2 generally show younger ages from the rim domain, consistent with Pb loss or addition of young metamorphic rims. Discordant dates obtained from both core and rim domains produce an array with a lower intercept age of ~190 to 130 Ma, that is, consistent with three of the rim analyses at 152–192 Ma (Figures 4e and 4f). On the basis of CL-textures, Th/U and evidence to isotopic disturbance, we interpret a relatively young (Mesozoic) post-depositional metamorphic history for this sample.

4.2.2. 17RAY-AP012B1

Sample 17RAY-AP012B1 (Figure 4g) is a foliated, chlorite-mica-schist collected from an outcrop mapped as Snowcap assemblage (Yukon-Tanana terrane, Figure 2). Sample 17RAY-AP012B1 yielded rounded to subrounded equant to elongate zircon with CL zoning ranging from oscillatory to fir-tree and patchy textures and common, thin (1–10 μm), CL-bright rims interpreted as metamorphic overgrowths (Data Set S1). Most grains show truncation of zoning by the grain boundary. Spot analyses were conducted on 309 zircon grains (including 10 fine rim ages). The five youngest accepted core analysis gave an age of 600 ± 35 Ma (2σ systematic error) was obtained from a rim analysis that may record the detrital igneous or metamorphic protolith or a mix of metamorphic rim and detrital protolith. The remaining 154 grains yielded interpreted detrital zircon ages ranging between Mesoproterozoic to early Paleoproterozoic, middle Paleoproterozoic to late Paleoproterozoic, and Mesoproterozoic to earliest Neoproterozoic (Figures 4g and 6d). Archean to Paleoproterozoic zircon have U concentration of 32–481 ppm and Th/U ratios of 0.09–1.86, whereas Mesoproterozoic to earliest Neoproterozoic zircon have U concentration and Th/U ratios of 133–964 ppm and 0.14–1.11, respectively. The probability distribution of detrital zircon ages (Figure 6d) shows clusters of Neoarchean, Siderian to Statherian, Calymmian, and Ectasian to Stenian ages, with age-peaks of 2,735 Ma (n = 16), 2,347 Ma (n = 4), 2,106 Ma (n = 14), 1,870 Ma (n = 36), 1,813 Ma (n = 30), 1,463 Ma (n = 10), 1,314 Ma (n = 11), 1,151 Ma (n = 7), and 1,029 Ma (n = 4). The youngest concordant single-grain zircon age of 922 ± 27 Ma (2σ systematic error) provides a maximum depositional age for this sample. The high degree of discordance observed in this sample (Figure 4g) is interpreted to reflect Pb
loss due to metamorphism; discordant dates produce an array with a poorly defined Paleozoic to Mesozoic lower intercept age (Figure 4g).

### 4.2.3. 17RAY-AP014A2

Sample 17RAY-AP014A2 (Figures 4c and 4d) is a foliated, biotite-schist with rare sillimanite collected from an outcrop presently mapped as the Ingenika Group (Cassiar terrane, Figure 2). Sample 17RAY-AP014A2 yielded rounded equant to elongate zircon with oscillatory zoning and thin (1–10 μm) CL-bright rims. Oscillatory zoning in equant grains is commonly truncated at the grain boundary which is overgrown by a CL-bright rim. Spot analyses on 320 zircon grains (including 20 dates measured via SIMS) generated a strongly discordant array of data; 184 of the measurements (58%) do not pass the discordance and uncertainty filters for detrital ages (Figures 4c and 4d). The remaining 136 grains yielded interpreted detrital zircon ages ranging between the Mesoarchean to early Paleoproterozoic, middle to late Paleoproterozoic, Mesoproterozoic, late Neoproterozoic, and Late Devonian to Middle Mississippian. Archean to Paleoproterozoic zircon have U concentration and Th/U ratios of 51–611 ppm and 0.17–1.98, respectively, whereas Mesoproterozoic to Neoproterozoic zircon have U concentration and Th/U ratios of 104–1,194 ppm and 0.11–1.64, respectively. The probability distribution of Precambrian zircon dates that pass the discordance filters produce statistically significant clusters of Neoarchean, Rhyacian to Siderian, and Orosirian to Statherian ages with age-peaks of 2,664 Ma (2σ systematic error; Figure 6a), 2,515 Ma (n = 4), 2,093 Ma (n = 15), 1,815 Ma (n = 36), 1,487 Ma (n = 8), 1,331 Ma (n = 8), 1,179 Ma (n = 19), and 1,091 Ma (n = 17; Figure 6b). The youngest detrital zircon core age of 568 ± 10 Ma (2σ systematic error) is interpreted as the maximum depositional age of this sample, while recognizing the potential effects of the pronounced degree of Pb loss observed in the detrital zircon population and the relatively high uncertainty (13%, 2σ analytical error) of the measured 206Pb/204Pb ratio for this analysis.

Spot analyses specifically targeting CL-bright zircon rims (n = 12) produced concordant and discordant results with most 206Pb/238U dates ranging from Late Silurian to Early Cretaceous and U and Th/U values of 72–3,066 ppm and 0.002–3.3, respectively. Four additional SIMS analyses targeting CL rim domains produced older discordant data that is interpreted to reflect analysis of mixed domains or Pb loss. A group of four concordant ages with low Th/U (0.01–0.1) define a Concordia age of 370 ± 4 Ma (2σ systematic error; MSWD = 2.5 for concordance and equivalence; Figure 5d). A single concordant SIMS rim analysis with a very low Th/U (0.003) yielded a 206Pb/238U age of 134 ± 5 Ma (2σ systematic error; Figure 5d) that when combined with two slightly discordant, low Th/U (0.002–0.003) LAICPMS analyses yields a 206Pb/238U weighted mean age of 130 ± 4 Ma (2σ systematic error; MSWD = 3.0). Discordant zircon in this sample produce arrays with poorly defined lower intercepts that converge upon the Late Devonian to Early Cretaceous rim ages (Figures 4c and 4d). On the basis of textural evidence for rim growth and low Th/U ratios we interpret these concordant and discordant rim dates as a record of zircon rim growth and Pb-loss during Late Devonian and Early Cretaceous metamorphism.

### 4.2.4. 17RAY-AP016A2

Sample 17RAY-AP016A2 (Figures 4a and 4b) is a weakly foliated marble with minor grains of quartz and mica collected from an outcrop of marble with sub-meter thick beds of muscovite-biotite schist (e.g., sample 17RAY-AP016C1), which is mapped as the Ingenika Group (Cassiar terrane; Figure 2). Sample 17RAY-AP016A2 zircon are subrounded, subhedral, equant to elongate grains. Most grains have well-defined core-rim relationships with oscillatory zoned cores overgrown by 1–30 μm thick CL-bright rims (Figure 5b). Spot analyses of 313 zircon grains produced 177 analyses (57%) that do not pass the discordance and uncertainty filters for detrital ages (Figures 4a and 4b). The remaining 135 grains yielded interpreted detrital zircon ages ranging between the Mesoarchean to early Paleoproterozoic, middle to late Paleoproterozoic, Mesoproterozoic, late Neoproterozoic, and early to late Neoproterozoic (Figure 6a). Precambrian zircon have concentrations of U ranging between 37 and 983 ppm and show no correlation with age. Ratios of Th/U range between 0.31 and 1.52 for Mesoarchean to Siderian zircon and 0.10–1.62 for latest Rhyacian to Ediacaran zircon. The probability distribution of Precambrian detrital zircon ages produces statistically significant clusters of Neoarchean to Siderian, and Orosirian to Statherian ages, with age-peaks of 2,664 Ma (n = 10), 2,567 Ma (n = 6), 2,506 Ma (n = 6), 1,850 Ma (n = 18), 1,765 Ma (n = 36), and 1,688 Ma (n = 8; Figure 6a). We interpret the 616 ± 21 Ma (2σ systematic error) detrital zircon age as a maximum depositional age for sample 17RAY-AP016A2, whereas the igneous crystallization age of 372 ± 5 Ma (2σ systematic error) from sample 17RAY-AP016C1 provides a minimum depositional age.
Analyses that targeted CL-bright rims and domains within grains yielded Middle Jurassic to Early Cretaceous dates (n = 19) accompanied by U concentrations of 19–699 ppm and Th/U ratios of <0.009, except for three outliers with Th/U ratios of 0.01–0.42. None of the rim dates pass the discordance and uncertainty filters applied for provenance analysis of detrital ages, but are interpreted here instead to record metamorphic rim growth on the basis of their CL response showing clear core/rim textures, low U concentrations, and low Th/U. Nine of the rim dates are concordant and the remaining 10 discordant dates define an array consistent with the combined effects of analysis of mixed metamorphic and igneous domains, Pb loss, and common Pb (Figure 5e). The concordant dates produce a spread of $^{206}\text{Pb} / ^{238}\text{U}$ ages between 171 ± 5 and 135 ± 3 Ma (2σ analytical error; Figure 5e). The five discordant Jurassic ages define a Concordia age of 166 ± 2 Ma (2σ systematic error; MSWD = 4.6 for concordance and equivalence). The four concordant Cretaceous grains define a Concordia $^{206}\text{Pb} / ^{238}\text{U}$ age of 139 ± 2 Ma (2σ systematic error; MSWD = 3.2 for concordance and equivalence). Discordant dates from the detrital population in this sample produce arrays with lower intercepts that converge upon these Jurassic-Early Cretaceous Concordia ages (Figures 4a and 4b). We interpret the Jurassic and Early Cretaceous rim ages to represent either one or two phases of post-depositional metamorphism (Figure 5e).

4.2.5. 17RAY-AP017A1

Sample 17RAY-AP017A1 (Figure 4h) is a foliated white quartzite collected from metasedimentary unit MMS2, structurally below the Dunite Peak ophiolite (Figure 2). This unit was assigned to the Finlayson assemblage of the Yukon-Tanana terrane by Parsons et al. (2017) and Parsons, Zagorevski, et al. (2018). The sample yielded a population of rounded, spherical to ellipsoidal zircon. CL images show zircon with bright cores and thin dark rims, plus cross-cutting CL-dark bands following fractures (Figure 5c). Well-developed oscillatory zoning is common and can be traced crossing from bright cores, through thin dark rims, to the boundaries of round grains (Figure 5c). Based on the continuity of zonation from core to rim and grain boundary, we interpret the dark rims and internal domains along cracks as a record of post-deposition fluid-mediated element diffusion, which occurred without significant metamorphic rim growth.

Spot analyses were conducted on 314 zircon grains; 44 of these measurements (14%) do not pass the discordance and uncertainty filters for detrital ages (Figures 4h and 6e). The remaining 270 grains yielded interpreted detrital zircon ages ranging between the latest Mesoarchean to early Paleoproterozoic, middle Paleoproterozoic to early Mesoproterozoic, and middle Mesoproterozoic to earliest Neoproterozoic (Figure 6e). Zircon accepted for provenance evaluation have concentrations of U and Th/U ratios of 13–991 ppm and 0.01–1.9, respectively, and show no correlation with age; four outliers have Th/U ratios of 2.0–3.6. Age distributions show clusters of latest Mesoarchean to Neoarchean, latest Siderian to earliest Rhyacian, late Rhyacian, Orosirian to Statherian, and late Stenian to earliest Tonian ages, with age peaks of 2,821 Ma (Figure 4a; Parson et al., 2018). The sample yielded a $^{206}\text{Pb} / ^{238}\text{U}$ age of 988 ± 18 Ma (2σ systematic error) as the maximum depositional age of this sample. Discordant zircon produce a poorly defined lower intercept of <200 Ma (Figure 4h).

4.3. Results: Whole Rock Geochemistry of Metasedimentary Units

Geochemistry of metasedimentary units is generally a poor indicator of tectonic settings (Armstrong-Altrin & Verma, 2005), but can provide some information on source areas. Samples in this study are characterized by variable CaO (calcite), SiO$_2$, and Al$_2$O$_3$ concentrations indicating a variety of sedimentary protoliths ranging from marble to quartzite. All of the samples are characterized by high Zr/Sc and Th/Sc ratios indicative of long-term weathering and sorting processes (Figure 7; McLennan et al., 1993). All metasedimentary samples show flat trace element profiles on Post-Archean Australian Shale and upper continental crust normalized plots suggestive of continental sedimentary sources that are variably diluted by detrital quartz or calcite (Figure 7). Specifically, sample 17RAY-AP017A1 is characterized by very high SiO$_2$, very low Al$_2$O$_3$, and high Zr concentrations suggesting that the parent sediment was largely composed of quartz with abundant zircon (Figure 7). This may be indicative of rogeny transport, or reworking of rogeny sediments. Sample 16RAY-AP077B1 is characterized by high Zr/Sc and Th/Sc ratios indicative of weathering and sorting processes, however it has low SiO$_2$ and high
MgO, FeO, Ni, and V (Figure 7). This sample may be a mixture of reworked continentally derived sediment and sediment derived primarily from one or more mafic volcanic sources.

5. Summary and Interpretation of U-Pb Zircon Geochronology and Whole-Rock Chemistry

5.1. Igneous Samples

17RAY-AP015A1 is an undeformed biotite-monzogranite intruded within the Ingenika Group of the Cassiar terrane; it has a crystallization age of 116 ± 2 Ma (2σ systematic error; Figure 3a), and a peraluminous geochemical composition (Figures 3c–3h). This sample is comparable in age and composition to local intrusions within the Cassiar and Yukon-Tanana terranes including the d’Abbadie pluton, Last Peak granite (Figure 2), Dycer Creek Stock, and the Big Salmon Batholith (Colpron, Israel, & Friend, 2016; Colpron, Israel, Murphy, et al., 2016; de Keijzer et al., 2000; Gallagher, 1999; Westberg et al., 2009). Plutonic rocks of this age and composition are common across south-central Yukon, and are assigned to the Cassiar magmatic suite (117–104 Ma, Colpron, Israel, & Friend, 2016). These and other Early to Late Cretaceous intrusions are typically associated with crustal thickening and subsequent collapse of the Cordilleran rogeny in Alaska, Yukon and northern British Columbia (e.g., Hart et al., 2004; Mair et al., 2006). This is consistent with the low Th/U ratios, high U concentrations and abundant xenocrysts reported from this sample, which may be explained by zircon growth during incongruent crustal anatexis.

17RAY-AP016C1 is a foliated and metamorphosed monzogranite within the Ingenika Group of the Cassiar terrane; it has a crystallization age of 372 ± 5 Ma (2σ systematic error; Figure 3b) and a peraluminous geochemical composition (Figures 3c–3h). Volcanic and plutonic rocks of similar age to 17RAY-AP016C1 are reported elsewhere in south-central Yukon from the Seagull group, which is associated with continental rifting and intra-plate magmatism (Beranek et al., 2016; Tempelman-Kluit, 2012), and the Earn Group, which is associated with back-arc rifting and subduction (Campbell, 1967; Cobbett et al., 2020). The peraluminous composition of sample 17RAY-AP016C1 (Figures 3c–3h) is compatible with both of those settings.

5.2. Metasedimentary Samples

5.2.1. Cassiar Terrane Samples

Detrital zircon populations in the samples 17RAY-AP014A2 and 17RAY-AP016A2 are dominated by middle to late Paleoproterozoic and Neoarchean zircon (Figures 6a and 6b). In addition, sample 17RAY-AP014A2 has a significant population of Mesoproterozoic zircon, whereas sample 17RAY-AP016A2 has minor populations of early Mesoproterozoic zircon (Figures 6a and 6b). Sample 17RAY-AP014A2 has a youngest Precambrian single-grain zircon age of 568 ± 10 Ma (2σ systematic error), whereas Sample 17RAY-AP016A2 has a youngest single-grain zircon age of 616 ± 21 Ma (2σ systematic error; Figures 6a and 6b).

5.2.2. Yukon-Tanana Terrane Samples

Detrital zircon populations in samples 16RAY-AP077B1, 17RAY-AP012B1, and 17RAY-AP017A1 are dominated by middle to late Paleoproterozoic and Neoarchean zircon (Figures 6c–6e). In addition, sample 17RAY-AP012B1 has a significant population of Mesoproterozoic zircon, whereas sample 16RAY-AP077B1 has a significant population of early to middle Mesoproterozoic and middle to late Neoproterozoic zircon, and sample 17RAY-AP017A1 has a minor population of latest Mesoproterozoic zircon (Figures 6c–6e). Samples 16RAY-AP077B1, 17RAY-AP012B1, and 17RAY-AP017A1, have youngest single grain zircon ages of 530 ± 14, 922 ± 27, and 988 ± 18 Ma, respectively (2σ systematic error; Figures 6c–6e).

5.3. Mesozoic Metamorphism

Detrital zircon in samples 16RAY-077B1 (Yukon-Tanana terrane), 17RAY-AP016A2, and 17RAY-AP014A2 (Cassiar terrane) record evidence of metamorphism during the Late Devonian and the Middle Jurassic to Early Cretaceous. In sample 17RAY-AP014A2, CL-bright zircon rims with low Th/U ratios yielded a Concordia age of 370 ± 4 Ma (2σ systematic error; MSWD = 2.5; n = 4; Figure 5d), which we interpret as a record of metamorphism which accompanied monzogranite emplacement (17RAY-AP016C1). A single concordant date from
Detrital zircon dataset - multi-dimensional scaling (K-S statistic)

![Detrital zircon dataset - multi-dimensional scaling (K-S statistic)](image)

**Figure 8.** (a) Statistical comparison of detrital zircon datasets using multi-dimensional scaling of the Kolmogorov-Smirnov statistic, D (plotted using DZmds1.10; Saylor et al., 2018). Statistical similarity between datasets is proportional to relative distances between data points. Solid- and dashed-lined arrows point to closest and second-closest neighbors, respectively (i.e., lowest D values). A Shepard plot showing the goodness of fit is presented (Supporting Information S1 (Figure S3). Similarity matrices for D and the cross-correlation coefficient, R, are presented in Data Set S1. (b) U-Pb zircon metamorphic rim dates from samples 17RAY-AP016A2 (Cassiar—blue), 17RAY-AP014A2 (Cassiar—red), and 16RAY-AP077B1 (Yukon-Tanana—yellow), with Concordia ages of 166 ± 2 and 139 ± 2 Ma (2σ systematic error) calculated from concordant ages in 17RAY-AP016A2. Large data points are interpreted as robust records of zircon growth during Middle Jurassic-Early Cretaceous metamorphism. Small data points are consistent with zircon growth during Middle Jurassic-Early Cretaceous metamorphism, but other explanations for these data are also possible (e.g., Pb loss or high common Pb). U-Pb monazite dates of Westberg (2010) from samples 07EW167 and 07EW169, collected from the Snowcap assemblage in the Mendocina Creek area (~10 km south of Dunite Peak) are displayed in gray for comparison. a metamorphic rim with a very low Th/U ratio yielded a 206Pb/238U age of 134 ± 5 Ma (Figure 5d), which is comparable to Early Cretaceous metamorphic zircon rim ages reported from 17RAY-AP016A2 (Figure 8b). Discordant zircon in sample 17RAY-AP014A2 produce arrays with poorly defined lower intercepts that converge upon the Late Devonian to Early Cretaceous metamorphic ages (Figures 4c and 4d).

Samples 16RAY-077B1 and 17RAY-AP016A2 record evidence of Middle Jurassic-Early Cretaceous metamorphism (Figure 8b). Zircon in these samples have CL-bright, low Th/U metamorphic rims, and overgrowths (Figures 5a and 5b). In Cassiar terrane sample 17RAY-AP016A2, concordant metamorphic rim ages range between 171 ± 5 and 135 ± 3 Ma (2σ systematic error) and define Concordia ages of 166 ± 2 Ma (2σ systematic error; MSWD = 4.6, n = 5) and 139 ± 2 Ma (2σ systematic error; MSWD = 3.2, n = 4; Figures 5e and 8b). The relatively high MSWD values are interpreted to reflect either a prolonged complex metamorphic history or incomplete characterization (i.e., low n) of the metamorphism. Nevertheless, evidence for Mesozoic metamorphism is clear. In addition to zircon rim growth and recrystallization, samples 16RAY-077B1, 17RAY-AP016A2, and 17RAY-AP014A2 also yielded a majority of discordant grains, which form arrays with Mesozoic lower intercept ages (Figures 4a-4f). In sample 16RAY-AP077B1, these lower intercepts converge upon ~190 to 130 Ma (Figures 4e and 4f). We interpret this discordance as a record of Pb-loss during Middle Jurassic-Early Cretaceous post-depositional metamorphism.

Our record of Middle Jurassic-Early Cretaceous metamorphism recorded by the Cassiar and Yukon-Tanana terranes in the Dunite Peak region (Figure 8b) is comparable to preliminary U-Pb monazite dates reported from the Yukon-Tanana terrane in the Mendocina Creek area, ~10 km south of Dunite Peak (Figure 8b; Westberg, 2010). Westberg (2010) analyzed two samples of Snowcap assemblage from the Dunite Peak area that yielded U-Pb monazite single-grain dates of 192 ± 26, 179 ± 9, 152 ± 18, and 143 ± 8–106 ± 8 Ma (n = 18; Figure 8b). The mid-Cretaceous monazite dates may indicate that metamorphism continued after our youngest metamorphic zircon age (135 ± 3 Ma; 2σ systematic error) at conditions not conducive to metamorphic zircon growth. We note that these younger monazite dates are consistent with two CL-bright zircon rim dates from sample 16RAY-077B1 that give 206Pb/238U dates of 95 ± 2 and 119 ± 2 Ma (2σ systematic error), and low Th/U. However, high common Pb and very large uncertainty in measured 206Pb/208Pb ratios from these two zircon dates means that we cannot be certain of their origin.

Elsewhere in south-central Yukon, similar ages of metamorphism are reported from the Yukon-Tanana terrane in the Finlayson Lake district (169 ± 2–142 ± 3 Ma), and from parautochthonous Laurentian units in the Australian Mountain domain (146 ± 3–118 ± 1 Ma; Berman et al., 2007; Staples et al., 2013, 2014, 2016). Similarly, parautochthonous units of the Hyland group in east Yukon record greenschist to amphibolite facies metamorphism during the Early Cretaceous, prior to 107 Ma (Moynihan, 2017). Collectively these data indicate a regionally significant period of metamorphism of the parautochthonous Laurentian margin and Yukon-Tanana terrane in Yukon from the Middle Jurassic to Early Cretaceous (e.g., Staples et al., 2016). We explore the regional tectonic significance of this metamorphic event in our discussion below (Section 6.2).
In contrast to the metamorphic overprint recorded by the Snowcap assemblage in the Dunite Peak region and neighboring areas, detrital zircon from our Finlayson assemblage sample 17RAY-AP017A1 are mostly concordant (86% of measurements), and show only minor evidence for Mesozoic Pb-loss, as indicated by CL-dark domains along cracks and grain boundaries, and a poorly defined lower intercept of <200 Ma (Figure 4b). Zircon in this sample show no textural evidence of post-depositional growth or recrystallization (Figure 5c). These differences may indicate that in the Dunite Peak region, a metamorphic discontinuity separates the Finlayson assemblage from the structurally underlying Snowcap assemblage.

6. Discussion

6.1. Detrital Zircon Provenance

In this section, we consider the provenance of our detrital zircon samples through comparison with regionally distinct pre-Mesozoic detrital zircon signatures reported from north Laurentia (Figures 6f and 6g; Hadlari et al., 2012, 2015), and west to southwest Laurentia (Jones et al., 2015; Matthews et al., 2018; Figures 6h and 6i). This includes a visual statistical comparison of datasets using multi-dimensional scaling of the Kolmogorov-Smirnov (K-S) statistic, \( D \) (Figure 8a), which describes the maximum difference between the cumulative distribution functions of two samples (\( D = 0–1 \), increasing with dissimilarity; e.g., Saylor & Sundell, 2016). Statistical comparison using the cross-correlation coefficient, \( R^2 \) (e.g., Saylor & Sundell, 2016), which describes the similarity in amplitude and shape of normalized probability age peaks of two samples (\( R^2 = 0–1 \), increasing with similarity), was also conducted, and shows similar results to the K-S statistic (\( D \); note that \( D \) and \( R^2 \) have an approximately inverse relationship). Values of \( D \) and \( R^2 \) are quoted below and presented in similarity matrices in Data Set S1 (calculated using Dzstats2.30; Saylor & Sundell, 2016).

Pre-Mesozoic sedimentary rocks of North Laurentia typically yield one of two distinct zircon age spectra identified by Hadlari et al. (2012, 2015) as North Laurentia Type 1 and Type 2 (Figures 6f and 6g; respectively, comparable to Lineage A and Lineage B of Lane & Gehrels, 2014). Type 1 signatures (Figure 6g) are dominated by zircon originally sourced from Paleoproterozoic (~1.8 to 1.9 Ga peak) magmatic and Archean cratonic basement in northern and/or central Laurentia, whereas Type 2 signatures (Figure 6f) are dominated by a spread of Mesoproterozoic zircon originally sourced from the Grenville rogeny in east to southeast Laurentia (Hadlari et al., 2012, 2015; Rainbird et al., 1992, 2017). Recurrences and mixing of these signatures in late Mesoproterozoic through to Paleozoic sedimentary rocks in North Laurentia reflect multiple episodes of sediment reworking and transport across central, to northern and northwestern Laurentia (e.g., Hadlari et al., 2012, 2015; Lane & Gehrels, 2014; Matthews et al., 2018; Rainbird et al., 1992, 2017).

In west to southwest Laurentia, pre-Mesozoic sediments are characterized by Precambrian zircon with late Paleoproterozoic (~1.6 to 1.8 Ga) and Early Mesoproterozoic (~1.3 to 1.5 Ga) ages (Figures 6h and 6i; Jones et al., 2015; Matthews et al., 2018). These spectra reflect primary or recycled zircon originally sourced from 1.6 to 1.8 Ga arc terranes and 1.34–1.48 Ga A-type magmatic rocks in the Yavapai-Mazatzal province (Utah-Colorado-Arizona-New Mexico), plus non-Laurentian early Mesozoic zircon deposited in the Mesoproterozoic Belt-Purcell basin (Idaho-Montana; Jones et al., 2015; Ross & Villeneuve, 2003; Whitmeyer & Karlstrom, 2007). A minority of late Mesozoic zircon (~1.0 to 1.3 Ga) in Neoproterozoic to Cambrian sediments (e.g., Facies B, Figure 6h) are sourced from the southern Grenville rogeny. Neoproterozoic magmatic assemblages (~0.51 to 0.78 Ga) associated with the break-up of Rodinia are common in west and southwest Laurentia (Balgord et al., 2013; Fanning & Link, 2004; Gaschnig et al., 2013; Keeley et al., 2013; Linde et al., 2017; Lund et al., 2003, 2010; Schmitz, 2011; Yonkee et al., 2014).

6.1.1. Sample 17RAY-AP017A1 (North Laurentia Type 1 Spectrum)

The detrital zircon signature of Finlayson assemblage sample 17RAY-AP017A1 (Figure 6e) is typical of published detrital zircon datasets from the Yukon-Tanana terrane (Cleven et al., 2019). Statistically, it is most comparable to the North Laurentia Type 1 spectrum (\( D = 0.24, R^2 = 0.63 \); Figure 8a), owing to its large peak of 1.8–9 Ga ages and lack of Mesoproterozoic or younger age peaks (Figures 6e and 6g). The tectonostratigraphic framework for the Yukon-Tanana terrane (Colpron, Nelson, & Murphy, 2006, 2007) assumes that the Finlaysen assemblage was deposited after the Yukon-Tanana terrane rifted from northwest Laurentian. The North Laurentia Type 1 spectrum of sample 17RAY-AP017A1 is therefore explained as reworked peri-Laurentian sedimentary basement rocks of the Snowcap assemblage. However, differences between our detrital zircon samples suggest
that Finlayson assemblage sample 17RAY-AP017A1 was not sourced from the structurally underlying section of Snowcap assemblage represented by sample 16RAY-AP077B1 ($D = 0.65, R^2 = 0.11$). This is consistent with differences in the metamorphic assemblages and whole-rock geochemistry of all these samples.

### 6.1.2. Samples 17RAY-AP014A2 and 17RAY-AP012B1 (North Laurentia Mixed Type 1 and 2 Spectra)

The Precambrian detrital zircon signatures of Cassiar terrane sample 17RAY-AP014A2 and Snowcap assemblage sample 17RAY-AP012B1 (Figures 6b and 6d) are statistically most-similar to each other ($D = 0.11, R^2 = 0.69$; Figure 8a), and comparable to some of the published zircon spectra from the Yukon-Tanana terrane (Gilotti et al., 2017; Pecha et al., 2016) and Windermere Supergroup (Lane & Gehrels, 2014; Matthews et al., 2018; McMechan et al., 2017). After each other, these samples are statistically most-similar to a North Laurentia mixed Type 1 + 2 spectrum ($D = 0.13, R^2 = 0.58–0.69$; equivalent to the “hybrid lineage” of Lane & Gehrels, 2014). These spectra probably reflect a mixture of locally sourced reworked sediments from North and/or Northwest Laurentia (Lane & Gehrels, 2014) The single Neoproterozoic age (568 ± 10 Ma; 2$\sigma$ systematic error) in Cassiar terrane sample 17RAY-AP014A2 (Figure 6b) is equivalent to the age of syn-rift volcanics reported elsewhere in the Windermere Supergroup (e.g., the Hamil volcanics and granitic clasts in the Spa Creek assemblage) and correlative strata (e.g., Colpron et al., 2002; Erdmer et al., 2001; Lund et al., 2010; Yonkee et al., 2014).

### 6.1.3. Sample 17RAY-AP016A2 (Ambiguous Provenance)

The detrital zircon signature of Cassiar terrane sample 17RAY-AP016A2 is characterized by 1.65–1.9 and 2.3–2.7 Ga zircon ages (Figure 6a). Whereas this spread of ages is comparable to the North Laurentia Type 1 spectrum, the age peaks differ; sample 17RAY-AP016A2 has a maximum peak at 1.75–1.80 Ga (Figure 6a), whereas the Type 1 spectrum has a maximum peak at 1.80–1.95 Ga (Figure 6g). Additionally, sample 17RAY-AP016A2 has a lack of detrital zircon ages between ~2.0 and 2.3 Ga, which are observed in the North Laurentia Type 1 spectrum, and samples 17RAY-AP012B1, 17RAY-AP014A2, and 17RAY-AP017A1. Likewise, a small peak of 1.3–1.4 Ga zircon and absence of 1.0–1.3 Ga zircon in sample 17RAY-AP016A2 is anomalous with respect to the North Laurentia spectra, but typical of the Yavapai region. Two Neoproterozoic zircon ages are of comparable age to igneous assemblages found in the Windermere Supergroup and elsewhere across western and northern Laurentia (e.g., Cox et al., 2018; Gordey, 2013; Macdonald et al., 2018; Pigage & Mortensen, 2004; Sandeman et al., 2014; Yonkee et al., 2014).

A statistical comparison of sample 17RAY-AP016A2 with the rest of our dataset produces ambiguous results (Figure 8a). The K-S statistic ($D$) indicates sample 17RAY-AP016A2 is most similar to samples 17RAY-AP017A1, 17RAY-AP014A2 and 17RAY-AP012B1 ($D = 0.27, 0.23,$ and 0.21) and the North Laurentian Type 1 spectrum ($D = 0.25$). In contrast, the cross-correlation coefficient ($R^2$) indicates sample 17RAY-AP016A2 shares some similarities with sample 16RAY-AP077B1 ($R^2 = 0.57$), and Facies B and the Belt-Purcell Supergroup ($R^2 = 0.51, 0.52$), and is less similar to the rest of the zircon spectra. We suggest that this ambiguity is reflected by the range of potential zircon source regions, which include the Belt-Purcell Basin (1.4–1.8 Ga) in central Laurentia, the Yavapai province (1.3–1.4 and 1.7–1.8 Ga) in south-central to southwestern Laurentia, and the Swift Current Anorganic Province (1.7–18 Ga) and Trans-Hudson rogeny (1.8–1.9 Ga) in north-central Laurentia (e.g., Jones et al., 2015; Matthews et al., 2018).

### 6.1.4. Sample 16RAY-AP077B1 (West Laurentia spectrum)

Snowcap assemblage sample 16RAY-AP077B1 (Figure 6c) has a detrital zircon age spectrum that is distinct from other samples reported here, and previously, from the Yukon-Tanana or Cassiar terranes (Figure 8a; Cleven et al., 2019; Lane & Gehrels, 2014; McMechan et al., 2017). The large contributions of 1.6–1.8 and 1.3–1.5 Ga zircon alongside the near-absent contribution of 1.0–1.3 Ga zircon (Figure 6c), indicates that sample 16RAY-AP077B1 cannot be explained by reworking of locally derived sedimentary rocks with a North Laurentia Type 1 ($D = 0.62, R^2 = 0.13$), Type 2 ($D = 0.33, R^2 = 0.08$), or mixed Type 1 and 2 signature ($D = 0.33, R^2 = 0.17$). Instead, sample 16RAY-AP077B1 is statistically most-similar to rocks from west and southwest Laurentia (Figure 8a), including (a) late Neoproterozoic to Cambrian strata of the parautochthonous Cordillera in Nevada-Idaho-Utah (Facies B, Figure 6h; $D = 0.11, R^2 = 0.80$); (b) the Belt-Purcell Supergroup in Idaho-Montana (Figure 6i; $D = 0.25, R^2 = 0.85$); and (c) the Yavapai-Mazatzal province in Utah-Colorado-Arizona-New Mexico (Figure 6i; $D = 0.26, R^2 = 0.83$; e.g., Jones et al., 2015; Matthews et al., 2018). In particular, the parautochthonous Cordillera units of the Windermere Supergroup in Nevada-Idaho-Utah region contain an abundance of ~0.51 to 0.78 Ga magmatic assemblages, which match the Neoproterozoic ages in sample 16RAY-AP077B1 (Balgord et al., 2013;
Fanning & Link, 2004; Gaschnig et al., 2013; Keeley et al., 2013; Linde et al., 2017; Lund et al., 2003, 2010; Schmitz, 2011; Yonkee et al., 2014). As such, we argue that the detrital zircon spectrum in sample 16RAY-AP077B1 is most easily explained by sediment sourced from the Nevada-Idaho-Utah region.

6.1.5. Implications of West Laurentia Zircon Spectra in the Yukon-Tanana Terrane

Piercey and Colpron (2009) proposed that the siliciclastic stratigraphic units of the Snowcap assemblage represent a continental fragment rifted from northwest Laurentia. If this were correct for the whole of the Snowcap assemblage, then the detrital zircon spectrum of sample 16RAY-AP077B1 would require a long-range drainage system that transported sediment ∼1,500 to 2,500 km northwards from the Nevada-Idaho-Utah region to NW Laurentia, without being contaminated by more local sediment sources. This is at odds with the lack of other sedimentary units with equivalent detrital zircon spectra reported from northwest Laurentia (e.g., Cleven et al., 2019; Matthews et al., 2018; McMechan et al., 2017).

Alternatively, sample 16RAY-AP077B1 may represent a portion of Snowcap assemblage that was deposited in or close to the Nevada-Idaho-Utah region. This is consistent with the low SiO$_2$ and high MgO, FeO, Ni, and V geochemical composition of sample 16RAY-AP077B1, which is suggestive of a sediment component sourced from a local mafic igneous source (e.g., the Yavapai province and Windermere Supergroup). This hypothesis, which is similar to the interpretations of Wernicke and Klepacki (1988), implies that at least some parts of the Yukon-Tanana terrane derived from the west Laurentian margin, adjacent to the Nevada-Idaho-Utah region. We note that the large volume of carbonate sedimentary units mapped across the Dunite Peak region (see also Westberg et al., 2009) is atypical for the Snowcap assemblage and may highlight a distinct sub terrane that is allochthonous with respect to the rest of the Yukon-Tanana terrane peri-Laurentian basement (e.g., Parsons, Coleman, et al., 2018; Ryan et al., 2014; van Staal et al., 2018).

Lastly, we note that prior to our study, the presence of 1.3–1.8 Ga zircon in Cretaceous strata of southern Alaska and British Columbia, led some authors to propose that those units were deposited on the southwest Laurentian margin, before being structurally translated northwards to their present-day location (e.g., Garver & Davidson, 2015; Matthews et al., 2017). Our new data imply that the basement strata of Yukon-Tanana terrane may have acted as a previously unrecognized source of 1.3–1.8 Ga zircon to NW Laurentia, following its accretion to Laurentia in the Mesozoic. At present, the significance of this source for the post-Paleozoic zircon provenance of Laurentia is unclear due to the scarcity of other Yukon-Tanana terrane samples with high concentrations of 1.3–1.8 Ga zircon.

6.2. Metamorphic Events During the Tectonic Evolution of the Northern Cordillera

Our new constraints from the Dunite Peak region provide evidence for a Late Devonian metamorphic and magmatic event recorded by the Cassiar terrane (17RAY-AP014A2 and 17RAY-AP016C1; Figures 3b and 5d), and a Middle Jurassic-Early Cretaceous metamorphic event (Figures 5e and 8b) recorded by both the Cassiar terrane (17RAY-AP014A2 and 17RAY-AP016A1) and Yukon-Tanana terrane (16RAY-AP077B1). We interpret the significance of these results for the tectonic evolution of the Northern Cordillera as follows:

6.2.1. Late Devonian to Middle Triassic

Late Devonian metamorphism (370 ± 4 Ma; 2σ systematic error—17RAY-AP014A2) and magmatism (372 ± 5 Ma; 2σ systematic error—17RAY-AP016C1) recorded by our Cassiar terrane samples are consistent with magmatism reported elsewhere from the Cassiar terrane (Beranek et al., 2016; Cobbett et al., 2020; Colpron, Israel, & Friend, 2016; Tempelman-Kluit, 2012), and temporally overlap with low-pressure metamorphism and magmatism recorded in the Yukon-Tanana terrane (Berman et al., 2007; Colpron, Israel, & Friend, 2016). This thermal event may reflect rifting of Snowcap assemblage units of the Yukon-Tanana terrane from the Laurentian margin during the Late Devonian-Early Mississippian (e.g., Colpron, Mortensen, et al., 2006; Nelson et al., 2013).

After Late Devonian-Early Mississippian rifting, an episode of deformation, high-pressure metamorphism, and magmatism was recorded by the Yukon-Tanana terrane during the Middle to Late Permian (Beranek & Mortensen, 2011; Berman et al., 2007; Erdmer et al., 1998; Gilotti et al., 2017; Mortensen, 1992b). Previous models interpreted this event as a record of Middle to Late Permian collision between the Yukon-Tanana terrane and Laurentia (Beranek & Mortensen, 2011; Mortensen, 1992b; Nelson et al., 2013). However, as noted
by Parsons, Zagorevski, et al. (2018), van Staal et al. (2018), Zagorevski et al. (2021), and Zagorevski and van Staal (2021), (a) there is no corresponding record of Permian collision in northwest Laurentian units that can be matched with the observations from the Yukon-Tanana terrane; (b) geochemical signatures of Middle to Late Permian magmatism on the Yukon-Tanana terrane (Klondike assemblage) are best explained by lithospheric extension, rather than arc magmatism; and (c) the arrangement of Permian suprasubduction ophiolites in the Slide Mountain terrane places the Yukon-Tanana terrane in a lower plate position during Permian collision. Consequently, those authors interpreted the Middle to Late Permian event as a record of collision between the Yukon-Tanana terrane and the Dunite Peak intra-oceanic arc (Parsons, Coleman, et al., 2018; van Staal et al., 2018). We have implemented the interpretations of Parsons, Zagorevski, et al. (2018) and van Staal et al. (2018) for pre-Jurassic events into our tectonic synthesis (Figure 9a), as they are most consistent with our independently constrained model for the Jurassic–Early Cretaceous evolution of the Northern Cordillera.

6.2.2. Late Triassic to Middle Jurassic—Intermontane Superterrane-Laurentia Collision

Post-Permian collisional events recorded in the Northern Cordillera correspond to, (a) early accretion of the Intermontane superterrane (including the Yukon-Tanana, Stikine, Quesnel, and Cache Creek terranes); and (b) late accretion of the Insular superterrane to Laurentia (Figures 9b–9g; Evenchick et al., 2007; Monger & Gibson, 2019; Nelson et al., 2013; Parsons, Zagorevski, et al., 2018). Our new data support this hypothesis, and are consistent with constraints from parautochthonous Laurentia in east Alaska, south-central Yukon, and southern British Columbia, which suggest collision between Laurentia and the Intermontane superterrane occurred during the Early to Middle Jurassic (e.g., Colpron et al., 1996; Dusel-Bacon et al., 2002; Evenchick et al., 2007; Monger & Gibson, 2019; Staples et al., 2016).

In the Yukon-Tanana terrane, widespread shortening and metamorphism occurred during the latest Triassic to Early Jurassic (~205 to 180 Ma), and to a lesser extent, during the Middle Jurassic (Figures 9b–9e; e.g., Berman et al., 2007; Clark, 2017; Colpron et al., 2015; Gaidies et al., 2020; Kellett et al., 2018; Logan & Mihalynuk, 2014; Mihalynuk et al., 2006; Nixon et al., 2020; Ryan et al., 2021; Staples et al., 2016). Crustal thickening was accommodated by intra-terrane shear zones such as the Yukon River shear zone (“A”—Figures 9b–9d; Parsons, Coleman, et al., 2018; Ryan et al., 2014, 2021), and was followed by rapid cooling and exhumation during the Early to Middle Jurassic (Figure 9e; e.g., Johnston et al., 1996; Joyce et al., 2015; Ryan et al., 2021).

In parautochthonous Laurentia, the earliest record of collisional deformation and metamorphism is recorded between 188 and 180 Ma in southern British Columbia and eastern Alaska (Colpron et al., 1996; Dusel-Bacon et al., 2002; Evenchick et al., 2007; Monger & Gibson, 2019), and at 171 ± 5 Ma in south-central Yukon (this study; “D”—Figures 9b–9d). This was followed by crustal thickening within the Selkirk fan and Omineca belt in southern British Columbia between 174 and 162 Ma, the timing of which is equivalent to the older modality of metamorphic zircon ages in our Cassiar terrane sample 17RAY-AP016A2 (“E”—Figure 9e; 171 ± 5–158 ± 4 Ma; Concordia age of 166 ± 2 Ma, n = 5). Foreland basin subsidence at ∼154 Ma followed (“F”—Figure 9f), as the Laurentian margin continued to underthrust the accreted Intermontane superterrane (Colpron et al., 1996, 1998; Evenchick et al., 2007; Gibson et al., 2005).

The 10–20 Myr gap between the earliest records of collision reported from the Yukon-Tanana terrane and the parautochthonous Laurentian units can be explained by two alternative models (Figures 9b–9d):

In Model I, metamorphism and deformation of the Yukon-Tanana terrane between ∼205 and 180 Ma signifies the onset of collision with the leading edge of the Laurentian margin (Model I—Figure 9b), now located in the subsurface, several 100 km west of the eastern edge of the Yukon-Tanana terrane (e.g., Calvert et al., 2017; Cook et al., 2004). In this model, records of collision recorded by parautochthonous Laurentian margin units between ∼205 and 180 Ma must remain buried in the subsurface, west of the present-day contact between the Yukon-Tanana terrane and the Laurentian margin (“C”—Figures 9b–9e).

Alternatively in Model II, latest Triassic-Early Jurassic metamorphism of the Yukon-Tanana terrane corresponds to a period of intra-terrane crustal thickening, which began prior to collision with the Laurentian margin (Model II—Figures 9c and 9d; e.g., Berman et al., 2007; Parsons, Coleman, et al., 2018; Ryan et al., 2014, 2021; van Staal et al., 2018). This event may correspond to collision between distinct sub-blocks of Yukon-Tanana terrane (YTT-A and YTT-B in Model II—Figure 9e; e.g., Parsons, Coleman, et al., 2018; Ryan et al., 2014, 2021), collision between the Quesnel and Stikine arcs (e.g., Colpron et al., 2015; Currie & Parrish, 1997; George et al., 2021; Nelson et al., 2013), or collision of Cache Creek terrane with the Stikine-Quesnel arcs (Logan & Mihalynuk, 2014).
Figure 9. Tectonic model for the assembly of the Northern Cordillera orogen between eastern Alaska and southern British Columbia. Events “A” to “J” are discussed further in main text. During the latest Triassic-Early Jurassic, two models are possible (b)–(d); we favor Model II (c) and (d) over Model I (b) see main text for discussion. Abbreviations. YRSZ, Yukon River shear zone; YTT, Yukon-Tanana terrane.
Within south-central Yukon and northern British Columbia, latest Triassic to Early Jurassic collision between YTT subterranes is consistent with (a) final chert deposition within the intervening Cache Creek terrane; and (b) the record of syn-collisional deposition in the Whitehorse trough between the Stikine and Quesnel arcs (“B”—Figure 9c; Colpron et al., 2015; Cordey, 2020; Kellett et al., 2018; Kellett & Zagorevski, 2021).

Furthermore, investigation of Models I and II is required in order to precisely constrain the timing of collision between the Yukon-Tanana terrane and the Laurentian margin. This is hindered by a lack of definitive evidence from the sedimentary and accretionary records, needed to constrain the timing of this collision. For example, the Slide Mountain terrane was originally interpreted as the accretionary record of Permian collision between the Yukon-Tanana terrane and Laurentia (e.g., Mortensen, 1992a, 1992b). However, recent studies demonstrated that the Slide Mountain terrane includes Permian upper plate, intra-oceanic arc assemblages, and must comprise rocks from two or more oceanic basins (Parsons, Zagorevski, et al., 2018; van Staal et al., 2018; Zagorevski et al., 2021). Similarly, the Early to Late Triassic Jones Lake Formation has been interpreted as an overlap assemblage deposited on, and post-dating collision between, Slide Mountain terrane and Paraautochthonous Laurentia (Beranek et al., 2010; Beranek & Mortensen, 2011). However, Parsons, Zagorevski, et al. (2018) highlighted significant differences in the detrital zircon content of Triassic samples over the Slide Mountain terrane (e.g., unimodal Mesozoic or bimodal Paleozoic and Mesozoic zircon age populations), verses Triassic samples overlying Paraautochthonous Laurentia (e.g., Archean to Mesozoic zircon populations). Furthermore, Parsons, Zagorevski, et al. (2018) argued that the detrital signatures of Triassic strata on the Laurentia margin may be explained by a dominantly Laurentian sedimentary source with minor contributions from the Stikine/Quesnel arc and are at best, consistent with, but not definitive evidence for, Late Triassic collision between the Intermontane superterrane and Laurentia. These issues remain unresolved and require further assessment. Given the present-day thrust-slice structure of the Northern Cordillera, the original suture zone and accretionary record of the Intermontane-Laurentia collision may remain buried beneath the Intermontane or Insular superterranes (“C”—Figures 9b–9e).

In the absence of definitive sedimentary constraints, the combined records of deformation and metamorphism from the Yukon-Tanana terrane and the Laurentian margin are consistent with their collision occurring sometime during the Early to Middle Jurassic and no earlier than ~205 Ma (e.g., Dusel-Bacon et al., 2002; Evenchick et al., 2007; Gordey, 2002, 2013; Hansen & Dusel-Bacon, 1998; Parsons, Zagorevski, et al., 2018; Plint & Gordon, 1997; Stevens et al., 1996; Tempelman-Kluit, 1979). Consideration of the 3D geometry of collisions in Models I and II adds further complexity that is beyond the interpretation of constraints presented in this study. For example, competing 3D models of oroclinal bending (e.g., George et al., 2021; Mihalynuk et al., 1994; Nelson et al., 2006) versus thrust-nappe emplacement and strike-slip displacement (e.g., Goldberg, 2020; Monger & Ross, 1971; Ryan et al., 2021; Wernicke & Klepacki, 1988; Yarnell et al., 1999) are entirely reliant upon a robust framework of terrane definitions. However, recent studies demonstrating the presence of subterranes, suture zones, and other structural or paleogeographic discontinuities within these terranes, based on faunal, geochemical or geochronological constraints, highlight inconsistencies in the current terrane framework that must be addressed before the structural assembly of the North Cordillera can be robustly interpreted in three dimensions (e.g., George et al., 2021; Goldberg, 2018, 2020; McGoldrick et al., 2017; Milidragovic & Grundy, 2019; Parsons, Coleman, et al., 2018; Parsons, Zagorevski, et al., 2018; Pecha et al., 2016; Ryan et al., 2014, 2021; van Staal et al., 2018; Zagorevski, 2019; Zagorevski et al., 2017; Zagorevski & van Staal, 2021).

### 6.2.3. Middle Jurassic to Early Cretaceous—Insular Superterrane-Laurentia Collision

Based on our model of Early to Middle Jurassic collision between the Intermontane superterrane and Laurentian margin, we favor a subsequent collision between the Insular superterrane and Laurentian margin (Figure 9f) during either the Middle Jurassic (e.g., Gehrels et al., 2009; McClelland et al., 1992; McClelland & Gehrels, 1990; Monger & Gibson, 2019; Saleebey, 2000; Yokelson et al., 2015), or the Late Jurassic to Early Cretaceous (e.g., Clennett et al., 2020; Sigloch & Mihalynuk, 2017). This is consistent with the prolonged record of deformation and metamorphism recorded by the Laurentian margin through the Jurassic and Early Cretaceous (Dusel-Bacon et al., 2002; Gibson et al., 2008; Hansen & Dusel-Bacon, 1998; Moyghan, 2017; Staples et al., 2013; Webster et al., 2020), including further growth of metamorphic zircon in sample 17RAY-AP016A2 (“G”—Figure 9f) between the Late Jurassic and Early Cretaceous (Figure 8b).

We note that the polarity of subduction and collision between Laurentia and the Insular terrane is disputed by current studies, and is beyond the scope of this study, as indicated on Figure 9f (e.g., Clennett et al., 2020;
Monger, 2014; Monger & Gibson, 2019; Pavlis et al., 2019; Sigloch & Mihalynuk, 2017). Interpretations of the sedimentary and accretionary record of this collision recorded in Nutzotin-Dezadeash-Gravina-Gambier Basins (“H”—Figure 9f) are central to this problem and continue to be debated in the most recent works (e.g., Lowey, 2019; Pavlis et al., 2019; Ricketts, 2019; Sigloch & Mihalynuk, 2017).

6.2.4. Early to Late Cretaceous—Orogenic Collapse

Finally, growth of younger metamorphic zircon in our Cassiar terrane samples (Figures 8b—17RAY-AP016A2—145 ± 3–135 ± 3 Ma, Concordia age of 139 ± 2 Ma; 2σ systematic error, n = 4; 17RAYAP014A2—134 ± 5 Ma, n = 1) and monazite in the Snowcap assemblage in the Dunite Peak region (143 ± 8–106 ± 8 Ma, Figure 8b; Westberg, 2010) was contemporaneous with retrograde metamorphism, partial melting, extension, and exhumation recorded by parautochthonous Laurentian units and the Yukon-Tanana terrane between ∼140 to 130 and ∼110 to 100 Ma (“I” and “J”—Figure 9g; e.g., Berman et al., 2007; Dusel-Bacon et al., 2002; Gibson et al., 2008; Staples et al., 2016; Vice et al., 2020; Webster et al., 2020). This occurred during emplacement of late-Early Cretaceous syn-to post-tectonic I- and S-type intrusions (“J”—Figure 9g; Sample 17RAY-AP015A1, this study; Colpron, Israel, & Friend, 2016; de Keijzer et al., 2000; Gallagher, 1999; Gibson et al., 2008; Hart et al., 2004; Mair et al., 2006; Monger & Gibson, 2019; Pavlis et al., 1993; Westberg et al., 2009; Zagoryevski & van Staal, 2021). We suggest that late Early Cretaceous extensional faulting may have been responsible for the apparent metamorphic discontinuity that we identified between the Finlayson and Snowcap assemblages in the Dunite Peak region (“I”—Figure 9g). The undeformed nature of our biotite-monzogranite sample suggests that this extensional deformation was probably complete in the Dunite Peak region by 116 ± 2 Ma (2σ systematic error). Staples et al. (2016) applied a similar interpretation of a late Early Cretaceous extensional event to the Australian Mountain domain in central Yukon, where a tectonic window exposes Laurentian margin units structurally underlying the Yukon-Tanana terrane. These observations suggest that late Early Cretaceous extensional faulting of the Intermontane superterrane and parautochthonous Laurentian units may be more widespread than previously documented.

7. Conclusions

This study presents new zircon U-Pb geochronology from the allochthonous Yukon-Tanana terrane and the parautochthonous Cassiar terrane from the Dunite Peak region of south-central Yukon. The key findings from our results are as follows:

1. An undeformed, peraluminous, calc-alkaline biotite-monzogranite intruded within the Cassiar terrane (sample 17RAY-AP015A1), yielded a crystallization age of 116 ± 2 Ma (2σ systematic error). We correlate this intrusion with the Cassiar magmatic suite (117–104 Ma), which is commonly observed intruding both the Yukon-Tanana and Cassiar terranes in Yukon, and probably corresponds to a late-orogenic phase of extension, recorded across the Northern Cordillera.

2. A foliated, peraluminous, calc-alkaline monzogranite schist within the Cassiar terrane (sample 17RAY-AP016C1) yielded a crystallization age of 372 ± 5 Ma (2σ systematic error). Based on similarities in age and composition, this metagranitic rock correlates with igneous assemblages from either the Earn Group or the Seagull group, and was probably emplaced during rifting of siliciclastic basement units of the Yukon-Tanana terrane from the Laurentian margin.

3. Detrital zircon spectra from Finlayson assemblage sample 17RAY-AP017A1, Snowcap assemblage sample 17RAY-AP012B1 (Yukon Tanana terrane), and Igenika Group sample 17RAY-AP014A2 (Cassiar terrane) are typical of northwest Laurentia. Sample 17RAY-AP017A1 is comparable to the North Laurentia Type 1 spectrum of Hadlari et al. (2012; equivalent to Lineage A of Lane & Gehrels, 2014), whereas samples 17RAY-AP012B1 and 17RAY-AP014A2 are comparable to the North Laurentia mixed Type 1 and Type 2 spectrum of Hadlari et al. (2012; equivalent to the “hybrid lineage” of Lane & Gehrels, 2014). Ingenika Group sample 17RAY-AP016A2 (Cassiar terrane) has an ambiguous detrital zircon spectrum, with similarities to both north and west Laurentian reference spectra. Potential source regions include the Swift Current anorogenic province and Trans-Hudson orogen, the Belt-Purcell Basin, and the Yavapai province. The detrital zircon spectrum from Snowcap assemblage sample 16RAY-AP077B1 (Yukon Tanana terrane) is anomalous to northwest Laurentia. Zircon ages in this sample are indicative of a sediment sourced from the Nevada-Idaho-Utah region, implying either (a) long range transport of sediment from Nevada-Idaho-Utah to northwest Laurentia, without contamination from more locally sourced sediment; or (b) sample
16RAY-AP077B1 and its outcrop of Snowcap assemblage in the Dunite Peak region were deposited in or close to the Nevada-Idaho-Utah region before rifting from the west Laurentian margin during the Devonian. The latter hypothesis implies that the Yukon-Tanana terrane comprises distinct sub-terranes with different paleogeographic origins that should be investigated further. Additionally, our data imply that the Yukon-Tanana terrane provided a previously unrecognized and potentially important source of Mesoproterozoic zircon to Mesozoic and younger units of NW Laurentia.

4. Discordant zircon and concordant metamorphic zircon rims in Ingenika Group sample 17RAY-AP014A2 (Cassiar terrane) records Pb-loss and zircon recrystallization during Late Devonian metamorphism. Four measurements produce a Concordia age of $370 \pm 4$ Ma ($2\sigma$ systematic error), which overlaps with magmatic age of our monzogranite sample 17RAY-AP016C1 ($372 \pm 5$ Ma; $2\sigma$ systematic error) from the Cassiar terrane. We interpret this magmatic and metamorphic event as a record of rifting of Snowcap assemblage units (Yukon-Tanana terrane) from the Laurentian margin.

5. Discordant zircon and concordant metamorphic zircon rims in Snowcap assemblage sample 16RAY-AP077B1 (Yukon-Tanana terrane) and Ingenika Group samples 17RAY-AP014A2 and 17RAY-AP016A2 (Cassiar terrane) record Pb-loss and zircon recrystallization during metamorphism between $171 \pm 5$ and $135 \pm 3$ Ma. These data produce Concordia ages of $166 \pm 2$ and $139 \pm 2$ Ma ($2\sigma$ systematic error). Combined with similar ages of metamorphism reported elsewhere in Yukon, eastern and southern Alaska, and British Columbia, these data highlight a regionally significant period of metamorphism of the parautochthonous Laurentian margin from the Middle Jurassic to Early Cretaceous. We interpret this metamorphism as a combined record of: (a) Early to Middle Jurassic collision between Laurentia and the Intermontane superrterane (including the Yukon-Tanana terrane), which began no earlier than ~205 Ma; and (b) Middle or Late Jurassic to Early Cretaceous collision between Laurentia and the Insular superrterane. Sample 17RAY-AP017A1 (Finlayson assemblage) shows only minor evidence for a Mesozoic Pb-loss event (<200 Ma), with no evidence of zircon recrystallization, suggesting that a metamorphic discontinuity separates this unit from the underlying Snowcap assemblage. This discontinuity may indicate the presence of an extensional detachment responsible for the exhumation of the Cassiar terrane, which is consistent with the record of Early Cretaceous retrograde metamorphism, exhumation, and crustal melting reported elsewhere in Yukon, eastern and southern Alaska, and British Columbia.

Finally, we note that consideration of the 3D geometry of collisions between Laurentia, the Intermontane, and Insular superrteranes adds a significant degree of complexity that is beyond the interpretation of constraints presented in this study. Determination of the 3D geometries of these collisional events depends crucially on a robust framework of terrane definitions. Mounting evidence for the presence of sub-terranes, suture zones, and other structural or paleogeographic discontinuities within terranes of the Northern Cordillera (particularly within the Intermontane terranes), demonstrate critically, that the current terrane framework must be revised before the 3D structural assembly of the North Cordillera can be robustly interpreted (e.g., George et al., 2021; Golding, 2018, 2020; McGoldrick et al., 2017; Milidragovic & Grundy, 2019; Parsons, Coleman, et al., 2018; Parsons, Zagorevski, et al., 2018; Pecha et al., 2016; Ryan et al., 2014, 2021; van Staal et al., 2018; Zagorevski, 2019; Zagorevski et al., 2017, 2021; Zagorevski & van Staal, 2021).

Data Availability Statement
Data presented in this study, including geochronology and geochemistry datasets are freely available at the University of Plymouth data repository, PEARL (Plymouth Electronic Archive and Research Library): Parsons, (2021).

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