ABSTRACT

Potassic feldspar-bearing augen granitoids are a fundamental component of the architecture of the Yukon-Tanana terrane and the ancient Pacific margin of the northern Cordillera. These augen granitoids form a belt that extends from Alaska to southeast Yukon Territory, vary in age, and provide probes of the crustal evolution and tectonic history of the Yukon-Tanana terrane and ancient Pacific margin of North America in the Paleozoic. We present results of an integrated field mapping, geochemical, Sm-Nd tracer isotope, and U-Pb zircon geochronologic study of the augen granitoids in the Stewart River area in an attempt to understand their role in the crustal evolution and tectonic history of the Yukon-Tanana terrane and ancient Pacific margin of North America in the Paleozoic. We present results of an integrated field mapping, geochemical, Sm-Nd tracer isotope, and U-Pb zircon geochronologic study of the augen granitoids in the Stewart River area in an attempt to understand their role in the crustal evolution and tectonic history of the Yukon-Tanana terrane and ancient Pacific margin of North America.

Augen granitoids of the Stewart River area are of three distinct ages: Late Devonian, early Mississippian, and Permian. U-Pb zircon geochronologic study of the augen granitoids has yielded ages of 362.1 ± 2.7 Ma (Stewart River augen granite), 347.5 ± 0.7 Ma (Mount Burnham augen granite), and 264.8 ± 3.7 Ma (Wounded Moose augen granite). All of the augen granitoids, regardless of age, have negative $\varepsilon_{Nd}$ values (−2.0 to −15.3) and Proterozoic-Archean depleted-mantle model ages ($T_{DM} = 1.37–2.56$ Ga). These geochemical and isotopic attributes, coupled with the presence of inherited zircon with Precambrian ages, suggest that these granitoids are the product of crustal melting and crust-mantle mixing during three different cycles of arc magmatism in the Paleozoic. Furthermore, these granitoids represent net crustal recycling along the ancient Pacific margin of North America in the Paleozoic. Importantly, however, there are minor secular variations in crustal recycling, and the younger Permian augen granitoids exhibit higher $\varepsilon_{Nd}$, Nb/Ta, V/Yb, and Sc/Yb, consistent with a greater juvenile component in their genesis. This juvenile component is probably due to assimilation of underplated mafic material derived from older early Mississippian Yukon-Tanana terrane arc magmatism and/or a greater mantle component due to enhanced infiltration of underplated mafic material into augen granitoid magma chambers through rheologically weak crust associated with Permian subduction.

The older Late Devonian and early Mississippian augen granitoid suites represent two pulses of Yukon-Tanana terrane arc magmatic activity that developed in response to east-dipping subduction along the western edge of the North America craton in the mid-Paleozoic. This east-dipping Yukon-Tanana terrane arc system continued to evolve throughout the Mississippian to Early Permian and was coincident with the development of the Slide Mountain backarc basin that formed between the Yukon-Tanana terrane arc system and the North American craton; this east-dipping arc-backarc system continued until ca. 275 Ma. After ca. 275 Ma, the east-dipping arc and backarc magmatism ceased and was replaced by ca. 270–269 Ma high-pressure metamorphism and the establishment of a new subduction zone that formed in response to the closure of the Slide Mountain backarc basin. The Permian augen granitoids from the Stewart River are the magmatic record of this new west-dipping subduction zone.

Although there are subtle variations, the petrogenetic and tectonic histories of the three suites of augen granitoids in the Stewart River area are remarkably similar and attest to the constancy of magmatic and tectonic processes that occurred along the ancient Pacific margin of North America in the Paleozoic.

Keywords: tectonics, Yukon-Tanana terrane, Nd isotope geochemistry, augen granitoid, crustal growth, magmatism.
INTRODUCTION

Convergent margins are locations of extensive interaction between mantle, crust, and subducted slab, and have an important role in the evolution of the crust and mantle of Earth (Condie, 1997; Kamber and Collerson, 2000; Pearce and Peate, 1995; Rudnick, 1995; Rudnick et al., 2000). Along these margins there is a competitive balance between new juvenile crustal additions via magmatism and accretion versus the recycling of crust into the mantle via subduction and within the crust via intracrustal differentiation and crust-mantle interaction (Armstrong, 1988; Condie, 1997; DePaolo et al., 1992; Patchett and Samson, 2004; Rudnick, 1995; Samson et al., 1989; Samson and Patchett, 1991). Plutonic rocks in these margins provide key probes to the relative roles of juvenile versus evolved contributions to crustal growth along convergent margins (Armstrong, 1988; Chappell and White, 1974; DePaolo et al., 1992; Ghosh, 1995; Hildreth and Moores, 1988).

Throughout the North American Cordillera, plutonic rocks of various ages have provided significant insight into the relative roles of juvenile versus evolved crust during Cordilleran evolution. In the northern Cordillera, most of these granitoid studies have concentrated on the Mesozoic and Cenozoic intrusive rocks (e.g., Armstrong, 1988; Cui and Russell, 1995; Driver et al., 2000; Friedman et al., 1995; Ghosh and Lambert, 1995; Hart et al., 2004; Mair et al., 2006; Morris and Creaser, 2003), and only minor studies have been undertaken on Paleozoic plutonic rocks (e.g., Grant, 1997; Piercey et al., 2003a; Stevens et al., 1995). Paleozoic plutonic rocks, however, make up a significant component of the Yukon-Tanana terrane and rocks of the pericratonic (or near-continent) terranes of the Cordillera and are key probes to the crustal evolution and crust-mantle interaction within these terranes. These plutonic rocks are also important recorders of the cyclical arc and backarc history of the ancient Pacific margin of North America in the mid- to late Paleozoic (e.g., Nelson et al., 2006; Piercey et al., 2006). Hence, understanding the plutonic history of these granitoid plutons is not only critical for understanding the evolution of the Yukon-Tanana terrane, but also the tectonic evolution and relative roles of juvenile versus evolved crustal contributions to crustal growth along this ancient convergent margin.

Within the Yukon-Tanana terrane, there are two main granitoid plutonic groups: (1) the metaluminous, calc-alkaline, early Mississippian Simpson Range plutonic suite and equivalents (Grant, 1997; Mortensen, 1992; Piercey et al., 2003a; Stevens et al., 1995); and (2) Devonian to Permian augen granitoid suites (Dusel-Bacon and Aleinikoff, 1985; Mortensen, 1992; Piercey et al., 2003a). Previous studies on the Simpson Range plutonic suite have illustrated that they are largely the product of crust-mantle interaction within a magmatic arc system (Grant, 1997; Mortensen, 1992; Piercey et al., 2003a; Stevens et al., 1995). In contrast, the knowledge base for the augen granitoids is much smaller (Dusel-Bacon and Aleinikoff, 1985; Dusel-Bacon and Aleinikoff, 1996; Piercey et al., 2003a). These augen granitoids occur in a broadly linear array and extend for ~600 km from the Big Delta–Eagle–Tanacross areas of east-central Alaska, to the Finlayson Lake area of southeastern Yukon (Fig. 1). They range in age from ca. 365 Ma to ca. 260 Ma (Dusel-Bacon and Aleinikoff, 1985; Dusel-Bacon et al., 2004; Mortensen, 1990; Piercey et al., 2003a). In this paper, we provide an integrated field, U-Pb geochronological, geochemical and radiogenic isotopic study of Devonian-Mississippian and Permian K-feldspar augen granitoids from the Yukon-Tanana terrane in the Stewart River area of western Yukon, Canada (Fig. 1). These granitoids are important in that they provide probes of the crustal and tectonic evolution along the ancient Pacific margin of North America for more than 100 m.y., and their temporal distribution provides the means to test secular variations in crustal recycling and juvenile contributions to crustal growth along the ancient Pacific margin of North America. The results of this paper have implications for not only the crustal evolution, recycling history, and tectonic evolution of the ancient Pacific margin of North America in the Paleozoic, but for other similar active continental margins in the ancient geological record.

REGионаl geological setting

The Stewart River area is located southwest of Tintina fault, near Dawson City (Fig. 1), in the Omineca crystalline belt of the northern Canadian Cordillera (Wheeler and McFeely, 1991). It is part of the pericratonic, or continent-proximal, Yukon-Tanana terrane, and lies in fault contact with North American cratonic strata to the northeast (Murphy et al., 2002; Murphy et al., 2006) (Fig. 1). To the west of the Yukon-Tanana terrane lie the accreted terranes that comprise the Intermontane, Coast, and Insular Belts, which were accreted to the Yukon-Tanana terrane and the North American craton in the late Paleozoic to Mesozoic (Wheeler and McFeely, 1991). The Stewart River area consists of a variety of rocks ranging in age from pre–363 Ma to Eocene (ca. 52 Ma) (e.g., Mortensen, 1990). Middle to late Paleozoic rocks are mostly amphibolite facies gneiss and schist, which contain at least two generations of transposition foliations (Ryan et al., 2003). These rocks are intruded by younger plutons of Jurassic, Cretaceous, and Eocene age, and are overlain by Late Cretaceous volcanic and sedimentary rocks of the Carmacks Group (Figs. 2 and 3) (Ryan et al., 2003).

The lowermost unit in the Stewart River area (Ryan and Gordey, 2001, 2002; Ryan et al., 2003) consists of metasiliciclastic rocks of pre–Late Devonian (to potentially Mississippian) age (Villeneuve et al., 2003), equivalent to the Snowcap assemblage elsewhere in the Yukon-Tanana terrane (Colpron et al., 2006). This package consists predominantly of psammites and quartzite, with lesser amounts of pelite and rare conglomerate (Ryan and Gordey, 2001, 2002; Ryan et al., 2003). Amphibolite with arc tholeiitic affinities (Piercey et al., 2005; Piercey et al., 2003b) stratigraphically overlies, and structurally interferes with, the metasiliciclastic rocks, and marble horizons are found in both the amphibolite and metasiliciclastic rocks (Ryan and Gordey, 2001, 2002; Ryan et al., 2003). Local occurrences of metamorphosed gabbro are interpreted to be comagmatic with the amphibolite (Piercey et al., 2003b; Ryan and Gordey, 2001, 2002; Ryan et al., 2003). The amphibolite and metasiliciclastic rocks are intruded by a complex of early Mississippian calc-alkaline (Piercey et al., 2006), metaluminous plutonic to orthogneissic rocks (Figs. 2 and 3). This metaplutonic complex is interpreted to represent an early Mississippian subvolcanic intrusive complex, is composed of metamorphosed diorite, tonalite, granodiorite, and monzogranite, and is equivalent to the Simpson Range plutonic suite (Ryan and Gordey, 2001, 2002; Ryan et al., 2003).

The augen granitoids of the Stewart River and surrounding area are of three ages: Late Devonian (ca. 363–360 Ma), early Mississippian (ca. 347 Ma), and Permian (ca. 260 Ma) (Fig. 2; Tables 1–2) (Mortensen, 1986, 1990; Villeneuve et al., 2003; this study). The Late Devonian suite of augen granitoids predates the metaluminous granitic suite and the amphibolite, and only intrudes the lowermost metasiliciclastic unit (see following). The early Mississippian suite of augen granitoids is coeval with the early Mississippian granitic orthogneiss, and the Permian suite forms a younger intrusive suite that intrudes all these older rocks, and is coeval with similar Permian plutonic rocks (Sulfur Creek orthogneiss) and metavolcanic rocks (Klondike Schist) near the Dawson City region to the north (e.g., Mortensen, 1990). The Permian suite is interpreted to represent a separate Late Permian volcano-plutonic arc complex (e.g., Mortensen, 1990, 1992; Ryan et al., 2003).
Figure 1. Paleozoic tectonic assemblages of the northern Cordillera showing regional distribution of K-feldspar augen granitoids. The Stewart River study area is outlined (modified after Colpron et al., 2003; Foster et al., 1994; Piercey et al., 2006; Silberling et al., 1992; Wheeler and McFeely, 1991). Lithotectonic terranes and assemblages: AA—Arctic Alaska (includes Endicott Mountains, North Slope, and Skagit allochthon); AG—Angayucham; CA—Cassiar; CO—Coldfoot (schist belt of southern Brooks Range); DL—Dillinger; IN—Innoko; MN—Minchumina; MY—Mystic; NA—North American miogeocline; NS—Nisling (includes Endicott Arm, Port Houghton, Tracy Arm); NX—Nixon Fork; PC—Porcupine; RB—Ruby; SD—Seward; SM—Slide Mountain–Seventymile (includes Chatanika); ST—Stikine (Asitka); TZ—Tozitna; WM—Windy-McKinley; WS—Wickersham (includes Chena River, Fairbanks schist); YTT—Yukon-Tanana. Other abbreviations: AK—Alaska; B.C.—British Columbia; D—Dawson; E—Eagle; Fb—Fairbanks; NWT—Northwest Territories; Wh—Whitehorse; WL—Watson Lake; T—Tok; YT—Yukon Territory. Blueschists and eclogite occurrences are from Dusel-Bacon (1994) and Erdmer et al. (1998).
Augen granitoids, Yukon

Legend

- Cretaceous to Eocene: Carmacks Group volcanic rocks and porphyries
- Jurassic to Cretaceous: Granodiorite to granite intrusions.
- Permian: K-feldspar augen granitoids.
- Devonian to Permian: K-feldspar augen orthogneiss. May have both Permian and Devonian bodies within.
- Devonian-Mississippian: Undivided plutonic orthogneiss, amphibolite, and metagabbro
- Late Devonian: K-feldspar augen granite
- Early Mississippian: K-feldspar augen granite (Mount Burnham)
- Pre-Late Devonian: Undivided mica-quartz and quartz-mica schist and carbonate.

Fault: motion undetermined

Figure 2. Bedrock geological map of the Stewart River area with locations of augen granitoids. Map was modified from Ryan et al. (2003).
TABLE 1. SUMMARY OF PREVIOUS U-Pb GEOCHRONOLOGY FOR AUGEN GRANITOIDS IN YUKON-TANANA TERRANE

<table>
<thead>
<tr>
<th>Augen granitoid</th>
<th>Age (Ma)</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Delta</td>
<td>362 ± 4 to 371 ± 3</td>
<td>Dusel-Bacon et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>Fiftymile Batholith</td>
<td>362.4 ±10.2/−5.5</td>
<td>Mortensen (1986)</td>
<td></td>
</tr>
<tr>
<td>Fiftymile Batholith</td>
<td>353 ± 4 and 356 ± 2</td>
<td>Dusel-Bacon and Aleinikoff (1996)</td>
<td></td>
</tr>
<tr>
<td>Mount Burnham orthogneiss</td>
<td>363.8 ± 1.5</td>
<td>Mortensen (1990)</td>
<td>Superseded by this paper</td>
</tr>
<tr>
<td>Grass Lakes granitoid suite</td>
<td>360.0 ± 1.0, 361.1 ± 3.3, and 357.3 ± 2.8</td>
<td>Mortensen (1992) and Murphy et al. (2006)</td>
<td></td>
</tr>
<tr>
<td>Permian body, western Stewart River map sheet</td>
<td>253.5 ± 2.2</td>
<td>Mortensen (1990)</td>
<td></td>
</tr>
<tr>
<td>Sulfur Creek orthogneiss</td>
<td>263.8 ± 3.8 and 262.4 ± 2.2</td>
<td>Mortensen (1986, 1990)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Stratigraphic column for the Yukon-Tanana terrane in the Stewart River area. Figure was modified from Colpron et al. (2006). Stratigraphic data are from Ryan and Gordey (2002) and Ryan et al. (2003). Arc—arc magmatic rock.
AUGEN GRANITOID SUITES

In the Stewart River region, the low percentage of outcrop exposure (<1%) results in speculative field relationships between augen granitoids and surrounding lithologies, and bona fide relationships are based on key localities where relationships can be readily observed and/or on regional-scale map relationships.

Classically, the augen-bearing rocks of the Yukon-Tanana terrane have been termed augen gneiss, and the rocks herein are coeval with rocks deemed augen gneiss by Dusel-Bacon and co-workers (Dusel-Bacon and Aleinikoff, 1985; Dusel-Bacon and Aleinikoff, 1996; Dusel-Bacon et al., 2006). In this paper, we term these rocks augen granitoids rather than augen gneiss. This terminology is chosen because the bulk of these rocks contains K-feldspar phenocrysts (augen) that are granitic but do not have gneissic textures, whereas others are deformed and gneissic with K-feldspar augen. Hence, by using the term augen granitoid, it implies a correlation with augen gneissic bodies in Alaska but also illustrates that the bulk of the bodies in the Yukon are deformed granitic plutons not dominated by gneissic textures.

Augen granitoids from the Stewart River are divided based on age into Late Devonian to Early Mississippian and Permian (Fig. 2; Table 1). In general, the westernmost portion of the Stewart River map area is dominated by Permian-aged augen granitoids, whereas the central to eastern portions of the Stewart River map sheet are composed of both Permian and Devonian-Mississippian-aged augen granitoids (Fig. 2). The Late Devonian and early Mississippian augen granitoids are less abundant than the Permian suites and include: (1) the early Mississippian (ca. 347 Ma) Mount Burnham orthogneiss; (2) the Late Devonian (ca. 365–360 Ma) Tenderfoot Creek augen orthogneiss intrusion near the confluence of the Stewart River with the Yukon River; and (3) the Late Devonian (ca. 365–360 Ma) Fiftyfathom Batholith in the northwestern portion of the Stewart River map and southwestern corner of the Dawson map sheet (Figs. 1 and 2; Tables 1 and 2; e.g., Mortensen, 1990). Devonian-Mississippian augen granitoids are also present in eastern Alaska (Dusel-Bacon and Aleinikoff, 1985, 1996) and southeastern Yukon (Piercey et al., 2003a) (Fig. 1).

The Devonian-Mississippian augen granitoids are granitic to granodioritic in composition, with coarse to megacrystic, bleached K-feldspar phenocrysts, ~7 mm to 5 cm in size, wrapped by quartz (often drawn out into bands), biotite, and muscovite (Fig. 4A). They contain quartz, K-feldspar, plagioclase, muscovite, biotite, and, more rarely, hornblende. Pinhead (1 mm) garnets are present at one locality. The intensity of augen development and gneissosity increases toward the margins of the intrusions (e.g., Mount Burnham), and the core of the intrusions is megacrystic rather than augenbearing. In places, the augen granitoids are strongly deformed and are almost mylonitic. Some augen granitoids represent a single phase of plutonism (e.g., Mount Burnham, Tenderfoot Creek), whereas others are polyphase. For example, the Fiftyfathom Batholith in Alaska contains one phase of K-feldspar augen gneiss with accessory apatite, zircon, and Fe-Ti oxides, and a second phase of lesser abundance with accessory garnet, titanite, apatite, zircon, and epidote (Dusel-Bacon and Aleinikoff, 1996). U-Pb zircon dating of this batholith also supports a polynuclear phase; phases yield ages ranging from 362 to 353 Ma (Table 1; Dusel-Bacon and Aleinikoff, 1996; Mortensen, 1986).

All of the Devonian-Mississippian augen granitoids intrude the lowermost unit of metasedimentary rocks of the Yukon-Tanana terrane. The intrusions have sharp margins, where visible, and dikes and sheets of augen granitoids crosscut the surrounding metasedimentary rocks and are partially transposed into

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**TABLE 2. U-Pb ZIRCON GEOCHRONOLOGY DATA FOR AUGEN GRANITOID OF THE STEWART RIVER AREA**

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Wt.</th>
<th>U</th>
<th>Pb</th>
<th>206Pb/238U</th>
<th>207Pb/235U</th>
<th>208Pb/232U</th>
<th>Age (Ma, ±2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VN-01–09 (Z7047; 63.2794°N, 139.2299°W)—Tenderfoot Creek augen granitoid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z1</td>
<td>78</td>
<td>517</td>
<td>31</td>
<td>20701</td>
<td>0.15</td>
<td>0.05384 ± 0.04%</td>
<td>356.3 ± 0.8</td>
</tr>
<tr>
<td>Z2</td>
<td>50</td>
<td>546</td>
<td>32</td>
<td>9477</td>
<td>0.16</td>
<td>0.05373 ± 0.08%</td>
<td>356.2 ± 0.7</td>
</tr>
<tr>
<td>Z3</td>
<td>92</td>
<td>611</td>
<td>36</td>
<td>12944</td>
<td>0.16</td>
<td>0.05376 ± 0.05%</td>
<td>358.0 ± 1.0</td>
</tr>
<tr>
<td>03RAY316A2 (Z7895; 63.4768°N, 138.6623°W)—Mount Burnham augen granitoid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z1A</td>
<td>7</td>
<td>734</td>
<td>31</td>
<td>1675</td>
<td>0.13</td>
<td>0.05152 ± 0.11%</td>
<td>258.8 ± 0.6</td>
</tr>
<tr>
<td>Z1B</td>
<td>19</td>
<td>479</td>
<td>20</td>
<td>3433</td>
<td>0.13</td>
<td>0.05149 ± 0.07%</td>
<td>255.9 ± 0.5</td>
</tr>
<tr>
<td>Z2A</td>
<td>8</td>
<td>815</td>
<td>34</td>
<td>1602</td>
<td>0.14</td>
<td>0.05163 ± 0.10%</td>
<td>255.4 ± 0.5</td>
</tr>
<tr>
<td>03RAYP037A1 (Z7897; 63.6943°N, 138.2827°W)—Wounded Moose augen granitoid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z1A</td>
<td>24</td>
<td>449</td>
<td>24</td>
<td>1134</td>
<td>0.10</td>
<td>0.05450 ± 0.13%</td>
<td>353.3 ± 0.7</td>
</tr>
<tr>
<td>Z1B</td>
<td>19</td>
<td>507</td>
<td>27</td>
<td>2641</td>
<td>0.06</td>
<td>0.05383 ± 0.08%</td>
<td>350.2 ± 0.7</td>
</tr>
<tr>
<td>Z2A</td>
<td>26</td>
<td>503</td>
<td>27</td>
<td>4113</td>
<td>0.04</td>
<td>0.05558 ± 0.06%</td>
<td>360.0 ± 0.7</td>
</tr>
<tr>
<td>Z3A</td>
<td>51</td>
<td>352</td>
<td>18</td>
<td>6334</td>
<td>0.03</td>
<td>0.05373 ± 0.05%</td>
<td>348.9 ± 0.7</td>
</tr>
</tbody>
</table>

Note: Latitude and longitude in NAD27.

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Mesozoic rocks of the Stewart River area include Early Jurassic to Cretaceous hornblende and/or biotite-bearing granitoid intrusions, Cretaceous sedimentary rocks, and Cretaceous volcanic rocks (Fig. 2). Jurassic and Cretaceous granitic plutons and dikes range in composition from syenogranite to monzogranite. Cretaceous rocks include lithic rudites that have been tentatively correlated with the Late Jurassic-Cretaceous Talutus Formation and volcanic rocks in the northwestern portion of the Stewart River area, but are most abundant in the western portion of the Stewart River area (Fig. 2).
the regional foliation. The intrusions contain xenoliths (up to 20–30 m wide) of the surrounding metasedimentary unit. Furthermore, along the margin of the intrusions (e.g., Mount Burnham), the metasedimentary wall rocks are variably metamorphosed, and metamorphic grade decreases outward from the intrusions. Proximal to the intrusions, the metasedimentary rocks have assemblages with kyanite, garnet, biotite, staurolite, plagioclase, and calc-silicate assemblages; these assemblages are present up to 50 m from the contact with the intrusions. Additionally, the augen granitoids are in some places structurally interlayered with amphibolite, undivided orthogneiss, and gabbro-ultramafic material (e.g., Tenderfoot Creek body; Fig. 2).

The Permian augen granitoids are very similar to the Devonian-Mississippian augen granitoids. They are granitic to monzonitic in composition, contain K-feldspar up to 5 cm in size (Fig. 4B), and have varying abundances of quartz, plagioclase, biotite, magnetite, with accessory epidote and allanite; allanite is notably absent in Devonian-Mississippian augen granitoids of the Stewart River area. The Permian augen granitoids are present over a greater lateral extent than Devonian-Mississippian augen granitoids. They occur primarily in a northwest by southeast striking belt, ~100 km in length, in the western portion of the Stewart River area (Fig. 2), and within the central and eastern portions of the area (e.g., Kirkman Creek, Wooded Moose Dome, and Sulfur Creek; Fig. 2). They occur as composite batholiths (e.g., Wounded Moose Dome and Sulfur Creek body; Fig. 2), linear belts of intrusions (e.g., western Stewart River map area; Fig. 2), and as pod-like forms (e.g., Kirkman Creek body and location 6 on Fig. 2). Unlike the Devonian-Mississippian suites, the Permian augen granitoids crosscut both the metasedimentary basement package and younger Devonian-Mississippian rocks (Fig. 2).

The Permian intrusions contain xenoliths and rafts of metasedimentary basement rock, gabbro-ultramafic rocks interpreted to be derived from Devonian-Mississippian amphibolite and gabbro, and tonalite-granodiorite interpreted to be from older early Mississippian intrusions (e.g., augen granite 3 in Fig. 2). The state of strain of the Permian intrusions is generally similar or slightly more developed than that of the Devonian-Mississippian intrusions (Fig. 4).

**U-Pb GEOCHRONOLOGY**

**Analytical Procedures**

Three augen granitoid samples from the Stewart River area were dated using U-Pb zircon geochronology at the Geological Survey of Canada.

![Figure 4. Photographs of augen granitoids from the Stewart River area: (A) Mount Burnham orthogneiss: K-feldspar phenocrysts are wrapped by bands of quartz, muscovite, and biotite forming augen structures. (B) A relatively unstrained K-feldspar augen granitoid from the Permian belt in the western portion of the Stewart River map sheet. (C) Wounded Moose augen granite: a mylonitized example of augen granitoid with relict K-feldspar phenocrysts.](image-url)
Augen granitoids, Yukon

Canada, Ottawa, Canada. Zircons were separated from the samples using standard separation and purification techniques (e.g., crushing, Willey table, heavy liquids, and magnetic separation). Zircon grains used for analysis were selected based on clarity, color, and lack of fractures. All zircons were air abraded prior to analysis to minimize discordance caused by Pb-loss (Krog, 1982). Following abrasion, photography, and final mineral selection, mineral fractions were analyzed by isotope dilution–thermal ionization mass spectrometry (ID-TIMS) following the methods summarized in Parrish et al. (1987). Data were reduced and errors were propagated using software written by J.C. Roddick; error propagation was done by numerical methods (Parrish et al., 1987; Roddick, 1987; Roddick et al., 1987). Error ellipses on concordia diagrams (Fig. 5) are shown at the 2σ (95% confidence) level of uncertainty. Final errors are indicated in Table 2. Linear regressions on the concordia diagrams were carried out using a modified York (1969) method that takes into account the scatter of the points about the line (see discussion in Parrish et al., 1987). All uncertainties were multiplied by square root of mean square of weighted deviates (MSWD) if probability of fit was less than 0.15 (York, 1969). Fraction letters shown on concordia diagrams are keyed to the fraction letters in Table 2. Previous U-Pb ages on augen granitoids are presented in Table 1, and the new results presented here are in accordance with previous ages.

Results

Sample VN0109

Sample VN0109 is augen granite with reddish-pink K-feldspar megacrysts in a dark biotite-hornblende–rich matrix collected from the Tenderfoot Creek augen granitoid (Fig. 2). This sample is the protolith for a band of mylonite in the vicinity. Although zircon is abundant in this sample, it is almost all poor-quality zircon with high amounts of fracturing that led to breakage during abrasion and suggested that postcrystallization Pb-loss was the mechanism for discordance. Three fractions of highest-quality zircon were selected, abraded, and analyzed, resulting in all three falling near concordia with 206Pb/238U ages of 358–356 Ma (Fig. 5A). Although not collinear (MSWD = 4.4), the proximity of all fractions to concordia, coupled with fraction Z3 being the most nearly concordant, suggests that a weighted average of 207Pb/206Pb ages would represent a conservative and robust interpretation. This results in an interpreted crystallization age of 362.1 ± 2.7 Ma for this unit.

Figure 5. U-Pb concordia plots for: (A) Devonian augen granite near Stewart River; (B) Mississippian Mount Burnham augen granite; and (C) Permian Wounded Moose augen granite.
Sample 03RAYP037A1
Sample 03RAYP037A1 is a quartz-muscovite-K-feldspar augen gneiss that was collected near the summit of Mount Burnham and is representative of the Mount Burnham body. Clear, colorless zircon containing colorless, bubble-like inclusions but with no visible cores gives a well-defined linear array from all four analyzed fractions. The lower intercept results in an age of 347.5 ± 0.7 Ma (Fig. 5B), which is interpreted to represent the crystallization age, whereas the upper intercept points toward 1.66 Ga (MSWD = 1.2), which is interpreted to be an inheritance age.

Sample 03RAY316A2
Sample 03RAY316A2 was collected near the Stewart River and represents highly strained augen granite, verging on orthogness. U-Pb isotopic systematics are almost identical to those in VN0109, except this sample gives a clear Permian age, anchored by fraction Z1A that slightly overlaps concordia at ca. 259 Ma. Because of the statistical basis and for consistency in data handling with VN0109, a weighted average of Pb/206Pb age of 264.8 ± 3.7 Ma (MSWD = 2.2) is interpreted as the best indication of the crystallization age and its error. It is possible that the Pb/206Pb/238U age of fraction Z1A may give a better indication of the age and, as such, 259 Ma would represent the minimum age estimate.

LITHOGEOCHEMISTRY AND ISOTOPE GEOCHEMISTRY
Sampling and Analytical Procedures
Samples of augen granite were collected during regional mapping in 2000–2003 to provide a selection of Late Devonian, early Mississippian, and Permian augen granitoids from the Stewart River area. In addition, existing geochemical and isotopic data have been compiled from Dusel-Bacon and Aleinikoff (1985) and Piercey et al. (2003a) for augen granitoids from Alaska and the Finlayson Lake area of Yukon, respectively. The collected sample set includes: (1) 32 Permian samples; (2) 2 Late Devonian samples (Tenderfoot Creek); and (3) 4 early Mississippian samples (Mount Burnham). Samples of the Permian Klondike Schist (n = 8) and Late Devonian–early Mississippian Fiftymile Batholith (n = 2) were also included in this study for comparison.

Analytical procedures for this study are similar to those described by Piercey et al. (2004). Samples collected in this study had weathered edges removed by diamond saw and were subsequently crushed in a steel-jaw crushe and a mild-steel crushing mill. Rock powders were analyzed by X-ray-fluorescence (XRF) for major elements (on fused discs), select trace elements (on pressed pellets: Ni, Co, Cr, V, Cu, Pb, Zn, As, Ga, Sr, Rb, Ba), and loss on ignition (LOI) at the University of Western Ontario (UWO), London, Ontario, Canada, following the methods outlined in Mata et al. (1998), Wu (1984), and Young (2002). Precision for XRF analyses, based on replicate analyses of NIST SRM 610, was less than ±2% for major elements (±5% for P2O5 and Na2O) and ±5–10% for trace elements (Mata et al., 1998; Wu, 1984, Young, 2002). Accuracy for XRF analyses based on analyses of U.S. Geological Survey standard basalt BHVO-1 as an unknown was typically less than ±10%, where most elements were ±5% of recommended values (Mata et al., 1998). The remaining trace elements and rare earth elements (REEs) were analyzed by inductively coupled plasma–emission spectrometer (ICP-ES) (Sc) and ICP-mass spectrometry (MS) (Nb, Ta, Zr, Hf, Y, Cs, Th, U, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) at the Ontario Geoscience Laboratories, Sudbury, Ontario, Canada, using a closed-beaker multiacid digestion prior to analysis (Burnham et al., 2002; Burnham and Schweyer, 2004). Precision and accuracy for trace-element analyses by ICP-ES and ICP-MS at the Ontario Geoscience Laboratories, Sudbury, Ontario, Canada, using a closed-beaker multiacid digestion prior to analysis (Burnham et al., 2002; Burnham and Schweyer, 2004; Lightfoot and Farrow, 2002; MacDonald et al., 2005). Representative augen granitoid analyses are presented in Table 3 and the full data set can be found in Table DR1.

Neodymium isotopic analyses were undertaken at the University of Alberta Radiogenic Isotope Facility using thermal ionization mass spectrometry (TIMS), following the methods of Creaser et al. (1997a) and Unterschutz et al. (2002). Values for the Geological Survey of Japan (GSJ) Shin Etsu Nd isotope standard yielded an average 143Nd/144Nd = 0.512107, which is equivalent to 0.511850 for the La Jolla standard (Tanaka et al., 2000). Initial 143Nd/144Nd ratios and εNd were calculated at 362, 347, and 260 Ma, the approximate ages of the different augen granite suites. The chondritic uniform reservoir (CHUR) values used for εNd calculations were 143Nd/144Nd = 0.512638 and 146Sm/144Nd = 0.1967 (Hamilton et al., 1983).

ALTERATION, METAMORPHISM, AND ELEMENT MOBILITY
Although attempts were made to collect least-altered samples, field and petrographic data for the augen granitoids illustrate that they have been exposed to variably intense polyphase deformation and amphibolite facies metamorphism, with local greenschist-grade metamorphic overprints (Ryan and Gordey, 2001, 2002; Ryan et al., 2003). Given these metamorphic conditions, most major elements (e.g., SiO2, Na2O, K2O, and CaO) and low field strength elements (LFE: Cs, Rb, Ba, Sr) may have been mobilized to varying degrees (MacLean, 1990). The major elements Al2O3, TiO2 (±P2O5), the transition elements (Cr, Ni, Sc, V), the high field strength elements (HFSE: Zr, Hf, Nb, Ta, Y), the REEs, and Th were likely immobile under these metamorphic conditions (e.g., Jenner, 1996; MacLean, 1990; Pearce and Cann, 1973; Rolinson, 1993; Wood, 1980). Notably, however, most of the augen granitoid samples have Na2O contents between 2% and 5% and Al2O3/Na2O < 10 (see Spitz and Darling, 1978; Fig. 6), suggesting that these augen granitoids are relatively fresh, consistent with their mineralogy. Furthermore, on Harker diagrams, most mobile major elements, except Na2O and K2O, and most mobile trace elements, except Rb, Cs, and Ba (not shown), exhibit coherent trends (Fig. DR1; see footnote 1), which suggest that these elements were largely immobile.

Since the major elements of the augen granitoids have likely been affected by alteration and metamorphism, they are not discussed in detail in this manuscript. In this paper, we have relied primarily on immobile elements and Sm-Nd isotopic geochemistry. Nevertheless, Harker plots and major-element attributes of the rocks are presented in the Data Repository (Data Repository Item 1 and Figs. DR1–DR2 [see footnote 1]).

RESULTS
The Late Devonian, early Mississippian, and Permian augen granitoids have broadly similar trace-element systematics. They have subalkalic Nb/Y (<0.7) and intermediate to felsic Zr/TiO2 values (Fig. 7A). They have variable Zr/Y and Zr-Nb systematics with signatures similar to calc-alkaline suites of magmas (Fig. DR3, see footnote 1). The primitive mantle–normalized patterns for the Devonian and Mississippian suites (with one exception, 02RAY212A1) have light REE (LREE)–enriched patterns with negative Nb, Ti, and Eu anomalies, relatively flat to weakly depleted heavy REE (HREE), and compatible element (Sc, V) depletions (Fig. 8). These
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<td>Mt. Burnham</td>
<td>Western Belt</td>
<td>Wounded Moose</td>
<td>Wounded Moose</td>
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Note: Coordinates are UTM zone 7, NAD 83.

†X-ray fluorescence (XRF) values substituted for inductively coupled plasma–mass spectrometry (ICP-MS) analyses with lower element abundances.
patterns, coupled with their Ce-Yb (Fig. 7B), Nb-Y (Fig. 7C), and Ta-Yb (Fig. DR3, see footnote 1) systematics, are similar to calc-alkaline rocks found in continental magmatic arc environments. These systematics are similar to the Alaskan augen granitoids, which are interpreted to reflect continental arc melts (Dusel-Bacon and Aleinikoff, 1985), but are somewhat different than the Grass Lakes Suite augen granitoids of the Finlayson Lake district (MacDonald et al., 2005; Piercey et al., 2003a), and some Alaskan augen granitoids, which represent rift-related magmatic rocks (Figs. 7–8; Dusel-Bacon et al., 2004; Piercey et al., 2003a).

The Devonian-Mississippian augen granitoids have $\varepsilon_{\text{Nd}}$ values ranging from $-10.7$ to $-15.3$ (Fig. 9; Table 4) and depleted-mantle model ages ($T_{\text{DM}}$) of 1.49–2.56 Ga (Fig. 9; Table 4; using the depleted-mantle model of Goldstein et al., 1984). The Permian augen granitoids have overlapping to slightly higher $\varepsilon_{\text{Nd}}$ values that range from $-2.9$ to $-14.0$ and depleted-mantle model ages of 1.37–2.09 Ga (Table 4; Fig. 9). Two samples from the Klondike Schist have similar isotopic attributes as the Permian augen granitoids, with $\varepsilon_{\text{Nd}} = -9.9$ to $-11.5$ and $T_{\text{DM}} = 1.64–1.90$ Ga (Table 4; Fig. 9). Both the Devonian-Mississippi and Permian augen granitoids have isotopic signatures that overlap the field for other Yukon-Tanana terrane felsic rocks (Fig. 9).

Even though the Devonian-Mississippi and Permian augen granitoids are very similar, there are some minor trace-element differences between the suites. For example, the Permian augen granitoids range toward slightly higher La/Sm$_{\text{UCN}}$ (UCN = upper crust–normalized) ratios when compared to the Devonian-Mississippian granitoids (Fig. 10A). Furthermore, the Permian augen granitoids have higher Zr/Ti ratios at a given Ti content (Fig. 10B); have higher Sc and V and associated Sc/Yb and V/Yb ratios (Fig. 10C); higher Nb/Ta ratios at a given Ta content (Fig. 10D); and slightly higher, but overlapping, $\varepsilon_{\text{Nd}}$ values (Fig. 9).

**DISCUSSION**

**Variations in Crustal Recycling Along the Ancient Pacific Margin of North America**

Understanding the relative contributions of mantle and crust in arc-related granitoid rocks is critical to understanding the relative roles of juvenile and evolved contributions to crustal growth in accretionary arc systems like the North American Cordillera (e.g., Armstrong, 1988; DePaolo et al., 1992). Granitoids can provide significant insight into the relative contributions of juvenile and evolved components, and can provide significant information on the nature of the basement from which the granitoids were derived or with which they interacted (e.g., Chappell and White, 1974; DePaolo et al., 1992; Huppert and Sparks, 1988). The augen granitoids of the Yukon-Tanana terrane in the Stewart River area provide important probes of the crustal recycling history of the ancient Pacific margin of North America, insight into basement sources, and are a test of whether (or not) there were secular variations in crustal recycling along this margin.

Our results clearly indicate that the augen granitoids of the Yukon-Tanana terrane have had significant crustal inheritance from ancient sources. Both the augen granitoids and temporally equivalent metavolcanic rocks of the Klondike Schist have trace-element (e.g., La/Sm$_{\text{UCN}}$ ~1) and Nd isotopic signatures ($\varepsilon_{\text{Nd}} = -15.6$ to $-2.9$ and $T_{\text{DM}} = 1.37–2.56$ Ga; Table 4; Fig. 9) that require significant recycling of ancient, likely Proterozoic, upper-crustal material. These results are in accord with other augen granitoids and felsic rocks in the Yukon-Tanana terrane that have upper-crust-like trace-element characteristics (Dusel-Bacon and Aleinikoff, 1985; Dusel-Bacon et al., 2004; Piercey et al., 2006, 2001), evolved Nd, Sr, and Pb isotopic attributes (Grant, 1997; Mortensen, 1992; Piercey et al., 2003a; Stevens et al., 1995), and inherited Proterozoic to Archean zircon (Mortensen, 1990, 1992; Murphy et al., 2006).

There are, however, secular variations in the amount of crustal recycling within the various suites of augen granitoids. The Devonian-Mississippian augen granitoids have the least radiogenic $\varepsilon_{\text{Nd}}$ values ($-10.7$ to $-17.9$) and lower, and more crust-like, Nb/Ta values ($-12$; Barth et al., 2000; Green, 1995; Figs. 9–10; Table 4), indicating a significant crustal component in their petrogenetic history. The Permian suites have higher $\varepsilon_{\text{Nd}}$ values ($-2.9$ to $-14.0$), higher Nb/Ta values, and higher Sc/Yb and V/Yb at a given Yb content, suggesting a greater component from mantle and mantle-derived material and lesser contributions from ancient, evolved crustal materials (e.g., Sun and McDonough, 1989; Figs. 9–10; Table 4).

Quantification of the relative contributions of juvenile versus evolved crust in these granitoids can be evaluated using the neodymium crustal index (NCI) of DePaolo et al. (1992):

$$\text{NCI} = \left(\varepsilon_{\text{Nd}} - \varepsilon_{\text{NdCC}}\right)\left(\varepsilon_{\text{NdMC}} - \varepsilon_{\text{NdCC}}\right)$$

where $\varepsilon_{\text{Nd}}$ is the $\varepsilon_{\text{Nd}}$ of the sample, $\varepsilon_{\text{NdMC}}$ is the $\varepsilon_{\text{Nd}}$ of the mantle component, and $\varepsilon_{\text{NdCC}}$ is the $\varepsilon_{\text{Nd}}$ of the crustal component. The NCI assumes that the augen granitoids are the result of mantle-crust mixing (DePaolo et al., 1992), and this value provides an estimate of the crustal input in the granitoids: values of 1 would suggest 100% crustal Nd and no mantle component, whereas a value of 0 would represent 100% mantle component and no crustal component. For the calculations, the mantle end member is the depleted mantle (DM) reservoir (Goldstein
Figure 7. Trace-element discrimination diagrams for the Stewart River augen granitoids and associated Yukon-Tanana terrane felsic magmatic rocks: (A) Zr/TiO₂ vs. Nb/Y plot of Winchester and Floyd (1977) as modified by Pearce (1996); (B) Ce vs. Yb plot for different magmatic arcs from Hawkesworth et al. (1993); and (C) Nb vs. Y granite tectonic discrimination diagram from Pearce et al. (1984). Data are from the Grass Lakes augen granites from Piercey et al. (2003a), the Alaskan granitoids from Dusel-Bacon and Aleinikoff (1985), and the Klondike Schist from Piercey and Mortensen (2005, personal commun.). CVZ—central volcanic zone; SVZ—southern volcanic zone.
Figure 8. Primitive mantle–normalized plots (primitive mantle values from Sun and McDonough, 1989) for Stewart River augen granitoids and associated Yukon-Tanana terrane felsic rocks: (A) Late Devonian augen granitoids—Stewart River; (B) Late Devonian augen granitoids—Fiftymile Batholith; (C) early Mississippian augen granitoids—Mount Burnham augen granitoid; (D) Permian augen granitoids; (E) Late Devonian augen granitoids—Grass Lake suite, Finlayson Lake region (data from Piercey et al., 2003a); (F) Permian Klondike Schist (data from S.J. Piercey and J.K. Mortensen, 2005, personal commun.); and (G) Late Devonian augen granitoids—Alaska (data from Dusel-Bacon and Aleinikoff, 1985).
et al., 1984) calculated at 362 Ma, 347 Ma, and 260 Ma, the augen granitoid crystallization ages. The crustal end member is the average of NIII (Nisutlin geochemical group III) Yukon-Tanana terrane sedimentary rocks of Creaser et al. (1997a), which are interpreted to be the best estimate of Yukon-Tanana terrane crustal basement. Other sedimentary rocks from Creaser et al. (1997a) (i.e., NI and NII groups) are clearly too juvenile to have been crustal sources for the Yukon-Tanana terrane augen granitoids (Fig. 9; Table 5). Using the NIII crustal end member, the Late Devonian augen granitoids contain 64% to 79% crustal Nd (average 74%), the early Mississippian augen granitoids contain 73% crustal Nd, and the Permian augen granitoids contain 39% to 72% crustal Nd (average 57%). These results, although overlapping, demonstrate a decrease in the amount of crustal recycling in the younger Permian suite.

Even though there are variations in the amount of crustal recycling, all augen granite suites have Proterozoic (to Archean) depleted-mantle model ages (Table 4; TDM = 2.56–1.32 Ga) and Proterozoic to Archean zircon inheritance (Dusel-Bacon and Aleinikoff, 1996; Mortensen, 1990; this study). These data clearly suggest that these granitoids, and other felsic rocks of the Yukon-Tanana terrane, represent a net upper-crustal recycling event during the evolution of the ancient Pacific margin of North America rather than new juvenile crustal growth.

**Tectonic Significance of the Augen Granitoids**

The Yukon-Tanana terrane has been recognized as a magmatic arc system that was built upon a continental substrate along the ancient Pacific margin of the North American craton in mid- to late Paleozoic time (e.g., Mortensen, 1992; Nelson et al., 2006). Although this terrane does exhibit evidence for a more southerly location for part of its history (e.g., presence of McCloud fauna in Middle Permian rocks of Yukon-Tanana terrane similar to those in southwestern USA; Nelson, 1993; Ross, 1969), it initially started its life as an arc system built on the northwestern edge of the North American cratonic margin (Nelson et al., 2006). Numerous lines point to a tie to the northwestern North American craton, including: (1) similarities in detrital zircon and Nd isotopic distributions in sedimentary rocks in Yukon-Tanana terrane and North American cratonic margin strata (Creaser et al., 1997a; Nelson et al., 2006, and references therein); (2) coincident Late Devonian to early Mississippian rift histories (Gordey et al., 1987; Nelson, 1993; Paradis et al., 1998; Piercey et al., 2004); (3) coincident timing of Late Devonian to

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**Figure 9.** Radiogenic isotopic attributes of the Stewart River augen granitoids and Klondike Schist: (A) $\varepsilon_{Nd} vs. \frac{^{147}Sm}{^{144}Nd}$ plot with isotopic data from Yukon-Tanana terrane (YTT) felsic, mafic, and sedimentary rocks. Data for Yukon-Tanana terrane felsic rocks are from Grant (1997), Stevens et al. (1995), and Piercey et al. (2003a). Data for mafic rocks are from Creaser et al. (1997a, 1999), Grant (1997), and Piercey et al. (2003a, 2004, 2002, and 2005, personal commun.). Data for sedimentary rocks are from Creaser et al. (1997a) and Grant (1997); and (B) Nd isotope evolution plot illustrating isotope evolution pathways for different augen granitoids from the Stewart River area. Depleted mantle (DM) model is from Goldstein et al. (1984).
Figure 10. Geochemical plots that discriminate between Devonian-Mississippian and Permian augen granitoids: (A) upper crust-normalized (UCN) La vs. Sm plot (upper crust values from McLennan, 2001); (B) Zr/Ti vs. Ti; (C) Sc/Yb vs. V/Yb; and (D) Nb/Ta vs. Ta.
early Mississippian magmatic and metallocenic events in the miogeoclinal and Yukon-Tanana terrane (Dusel-Bacon et al., 2004; Nelson et al., 2002; Paradis et al., 1998; Piercey et al., 2001); (4) U-Pb zircon and Nd isotopic inheritance patterns in Yukon-Tanana terrane felsic rocks similar to those found in miogeoclinal rocks (Mortensen, 1992; Piercey et al., 2003a; this study); and (5) similar Pb isotopic signatures in syngenetic massive sulfide deposits in the miogeoclinal and Yukon-Tanana terrane (Mortensen et al., 2006). Collectively, these results all suggest that this arc system developed on the distal edge of the North American craton in the mid-Paleozoic in a broadly similar position to where it presently resides (Nelson et al., 2006).

The Yukon-Tanana terrane arc system, however, was an episodic arc system that had numerous cycles of arc and backarc magmatism (Nelson et al., 2006; Piercey et al., 2006; Simard et al., 2003). The Late Devonian suite of augen granitoids from the Stewart River area is part of the first phase of west-facing arc-related magmatism within the Yukon-Tanana terrane and represents the first arc-related granitic magmatism along the ancient Pacific margin of North America (Piercey et al., 2006; Fig. 11). This first phase of arc-related augen granitoid magmatism was also coincident with arc-related mafic magmatism in both the Stewart River area and other parts of the Yukon-Tanana terrane (Piercey et al., 2004, 2003b). It was also coincident with backarc rift- and continentalrift-related augen granitoids, felsic volcanism, mafic magmatism, and hydrothermal activity (e.g., Selwyn Basin sediment-hosted Pb-Zn and Yukon-Tanana terrane volcanogenic massive sulfide [VMS] deposits) elsewhere along the northern Cordilleran margin in both the Yukon-Tanana terrane and North American margin (Dusel-Bacon and Cooper, 1999; Dusel-Bacon et al., 2004; Nelson et al., 2002; Paradis et al., 1998; Piercey et al., 2001, 2002, 2003a, 2004). This initial arc rift event represented the initial phase of Slide Mountain ocean opening between the Yukon-Tanana terrane arc and the North American craton (Fig. 11) and is similar to the Miocene to Holocene development of the Japan islands and Japan Sea backarc basin (Nelson, 1993; Nelson et al., 2006; Piercey et al., 2004, 2006).

This initial Late Devonian arc magmatism continued into the early Mississippian (365–347 Ma) and was broadly similar in character to the Late Devonian magmatic event (Fig. 11; Piercey et al., 2006). The Mount Burnham augen granitoid is part of this second magmatic cycle and is part of one of the most voluminous episodes of arc magmatism during the Paleozoic evolution of the Yukon-Tanana terrane, where magmatism occurred over an area extending from eastern Alaska through northern British Columbia (Nelson et al., 2006; Piercey et al., 2006). The arc magmatism was also coincident with arc- and backarc basin magmatism, hydrothermal activity (e.g., Wolverine VMS deposit), and the continued opening of the Slide Mountain backarc basin and separation of the Yukon-Tanana terrane arc from the North American cratonic margin (Nelson, 1993; Nelson et al., 2006; Piercey et al., 2001, 2003a, 2006).

The evolution of the west-facing Yukon-Tanana terrane arc and backarc system continued throughout most of the Paleozoic (ca. 342–269 Ma) and involved continued magmatism in the Yukon-Tanana terrane and opening of the Slide Mountain backarc basin (Fig. 11; Nelson, 1993; Piercey et al., 2006; Simard et al., 2003). In Permian rocks of the Slide Mountain and Yukon-Tanana terrane, however, are Permian McCloud fauna (Nelson, 1993; Ross, 1969), requiring that by Middle Permian times, the Slide Mountain backarc basin and associated Yukon-Tanana terrane arcs had migrated to a more southerly latitude (Nelson et al., 2006). The Slide Mountain backarc basin likely reached its maximum width by ca. 275 Ma, the age of the youngest rocks in the Slide Mountain terrane (Murphy et al., 2006). At ca. 272–269 Ma (the age of first eclogite and blueschist formation from rocks of the Slide Mountain terrane), there was a fundamental shift in the dynamics of the Yukon-Tanana terrane–Slide Mountain arc-backarc system as west-facing Yukon-Tanana terrane arc magmatism abated and the Slide Mountain ocean began to close (Fig. 11; Creaser et al., 1997b; Erdmer et al., 1998; Mortensen, 1992). The closure of the Slide Mountain ocean toward the west resulted in the initiation of a new, west-dipping subduction zone, high-pressure metamorphism, and the development of a Permian arc system, represented by the linear belts of Permian augen granitoids and the metavolcanic rocks of the Klondike Schist in the Stewart River and Dawson City areas (Fig. 11; Creaser et al., 1997b; Erdmer et al., 1998; Mortensen, 1990, 1992). Coeval blueschists and eclogites occurring to the east of this Permian arc magmatic belt support the hypothesis that this subduction zone was west-dipping (Fig. 11; Creaser et al., 1997b; Erdmer et al., 1998; Mortensen, 1990, 1992). It also suggests that the Permian augen granitoids represent a pulse of magmatism built upon a pre-existing Devonian-Mississippian arc complex that included older augen granitoids.

The east-facing arc system represented by the younger augen granitoids continued until the accretion of the Yukon-Tanana terrane and Slide Mountain terranes to the North American craton in the Early Triassic (Beranek and Mortensen, 2006; Murphy et al., 2002, 2006; Nelson et al., 2006). The presence of Early Triassic foreland basin clastic rocks within the North American craton that have Yukon-Tanana terrane and Slide Mountain terrane lithostratigraphical and detrital zircon provenance (Beranek and Mortensen, 2006) suggests that these terranes were largely in their present position by the Early Triassic. It also suggests that there must have been northerly translation of the Yukon-Tanana terrane arc system between the Permian and Early Triassic from more southerly latitudes associated with Slide Mountain backarc basin closure (Nelson et al., 2006).

It is notable that throughout the development of the Yukon-Tanana terrane arc and backarc system, the augen granitoids acted as probes to crustal evolution and had significant, but variable, contributions from continental crust, with the Permian suite having a greater juvenile contribution (e.g., Table 4; Figs. 9–10). This greater juvenile component may have been the result of: (1) the assimilation of pre-existing intermediate to mafic Devonian-Mississippian–aged crustal material; or (2) greater mantle contributions to the granitoids during the Permian arc event. Abundant, primarily early Mississippian–aged intermediate to mafic magmatic rocks are present in the Stewart River area (Ryan and Gordan, 2001, 2002; Ryan et al., 2003). It is possible that this early Mississippian mafic magmatism may have caused mafic underplating of the crust.
which was then subsequently assimilated and incorporated into the partial melts that formed the Permian augen granitoids. Alternatively, a greater mantle contribution during the Permian arc event may have been due to the rheologically weaker state of the crust underlying the Yukon-Tanana terrane arcs in the Permian compared to the more rigid state in Late Devonian–early Mississippian times. In the Late Devonian, the crust underlying the Stewart River had not been modified or weakened by any significant tectonism since the breakup of Rodinia at ca. 720 Ma (e.g., Harlan et al., 2003). During the development of the Late Devonian–early Mississippian augen granitoids, and ensuing rifting related to the development of the Slide Mountain ocean, the crust underlying the Stewart River area was under significant extension and was attenuated and weakened relative to its pre–Late Devonian state. During Permian arc development, this thinned and weakened crust could have allowed for greater penetration by mantle-derived magmas, and as a result, greater mantle contributions to the Permian augen granitoids. It is possible
that both mechanisms could have played a part in producing Permian augen granitoids with a greater juvenile component.

CONCLUSIONS

Augen granitoids of the Stewart River area of the Yukon-Tanana terrane are probes of the crustal and tectonic evolution of the ancient Pacific margin of North America in the Paleozoic. The augen granitoids represent three distinctive arc magmatic pulses (Late Devonian, early Mississippian, and Permian) along the ancient Pacific margin of the North American craton and are related to the evolution of a poly cyclic Paleoarcear arc-backarc system along this margin. The different augen granitoids have major- and trace-element concentrations with Sm-Nd isotopic systematics (e.g., negative εNd values, Proterozoic-Archean depleted-mantle model ages) and inherited zircons consistent with significant crustal inheritance. Throughout the entire evolution of the ancient Pacific margin, these augen granitoids represent a net crustal recycling event rather than juvenile crustal growth. There are, however, notable differences in the amount of crustal recycling within the different suites—the Permian suites have higher εNd values, higher Nb/Ta, Sc/Yb, and V/Yb values, and higher Zr/Ti and La/Sm values consistent with a greater juvenile component in their genesis as compared to the older augen granitoid suites. The greater juvenile component in the younger suite is interpreted to be a product of: (1) the assimilation of older mafic-intermediate material that was upwelded to the Yukon-Tanana terrane arc in the early Mississippian; and/or (2) from greater infiltration of mafic magma into the crustal magma chambers due to rheological weakness of the arc crust associated with Permian arc magmatism.

The geological setting, U-Pb geochronology, geochemistry, and Sm-Nd isotope systematics of the Stewart River augen granitoids are the remnants of three superposed magmatic arcs of Late Devonian, early Mississippian and Permian ages. The first two episodes of arc magmatism occurred over an east-dipping subduction zone built on the margin of the North American craton during the Devonian-Mississippian that involved the formation of a Yukon-Tanana terrane arc system and a backarc basin, the Slide Mountain ocean, that opened between the North American craton and the Yukon-Tanana terrane arc system. The Yukon-Tanana arc system and Slide Mountain ocean continued to evolve throughout most of the Devonian through Early Permian reaching its maximum width by Early Permian (ca. 275 Ma). At this point, a fundamental shift in the architecture of this margin occurred as the Slide Mountain ocean started to close at ca. 270 Ma, which then resulted in an arc developing due to westward subduction of the Slide Mountain backarc basin. All three episodes of augen granitoid magmatism represent different arc magmatic cycles, with each episode autochthonously building on the previous arc sequence. Even though there were varying amounts of crustal material involved in granitoid genesis, during all of these magmatic episodes there was a consistent ancient (likely Proterozoic) crustal component in the granitoid suites.

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