An orogenic wedge model for diachronous deformation, metamorphism, and exhumation in the hinterland of the northern Canadian Cordillera

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ABSTRACT

Development of amphibolite-facies transposition fabrics in the northern Canadian Cordilleran hinterland occurred diachronously in the Permian–Triassic, Early Jurassic, Middle Jurassic to Early Cretaceous, and Early to mid-Cretaceous. Rocks tectonized in the Permian–Triassic and Early Jurassic were exhumed in the Early Jurassic, while rocks immediately to the northeast (toward the foreland) were not buried and heated until the Middle Jurassic to mid-Cretaceous. Early Jurassic to mid-Cretaceous emplacement of the Yukon-Tanana terrane on the North American continental margin, together with the imbrication of parautochthonous rocks, formed a foreland-propagating orogenic wedge. Cooler rocks in front of the wedge were progressively buried and metamorphosed to amphibolite facies from the Jurassic to mid-Cretaceous as they were underthrust into a spatially and temporally transient distributed ductile shear zone near the base of the overriding wedge. Rocks previously incorporated into this zone were displaced upward and exhumed through the combined effects of renewed underplating at depth and compensating extensional and erosional denudation above to maintain a critically tapered wedge. Extensional exhumation of the metamorphic hinterland in the mid-Cretaceous marked the collapse and end of orogen-perpendicular wedge dynamics in operation since the Early Jurassic. Rocks incorporated into the midcrustal shear zone in the Middle Jurassic to mid-Cretaceous were exhumed in the mid-Cretaceous along southeast-directed (orogen-parallel) extensional faults from beneath a supracrustal "lid" tectonized in the Permian–Triassic and Early Jurassic. Like the Himalayan orogen and eastern Alps, orogen-parallel extension developed in an orthogonal plate-convergent setting, simultaneous with, and bounded by, orogen-parallel strike-slip faulting that facilitated northwestward lateral extrusion of rocks normal to the direction of convergence.

LITHOSPHERE; v. 8; no. 2; p. 165–184 | Published online 25 January 2016 doi:10.1130/L472.1

INTRODUCTION

Deformation and metamorphism are commonly diachronous across orogens, with multiple overprinting events. Williams (1985) illustrated the difficulty of correlating such events throughout an orogen only on the basis of structural overprinting, style, pattern of orientation, and relationship of fabrics to metamorphic minerals and assemblages. However, understanding how deformation and metamorphism vary temporally throughout the orogen is critical to our understanding of the tectonic processes operating in orogenic belts.

Advances in phase equilibria modeling and in situ geochronological techniques present an opportunity to link the timing of accessory mineral growth (e.g., monazite) not only to specific porphyroblasts and associated pressure-temperature (*P-T*) conditions (e.g., Foster et al., 2002, 2004; Gibson et al., 2004), but also to specific deformation fabrics (e.g., Williams and Jercinovic, 2002; Berman et al., 2005, 2012). The application of these techniques makes it possible to definitively correlate or differentiate metamorphic and deformational fabrics within an area or across an orogen. For example, application of these techniques has facilitated identification of multiple metamorphic events in terrains that have been intensely reworked (e.g., Cutts et al., 2010; Berman et al., 2010, 2012). Furthermore, this approach has revealed domains with contrasting pressure-temperature-time-deformation (*P-T-t-D*) histories that were previously considered a single tectono-metamorphic unit (Crowley et al., 2000; Berman et al., 2007; Horváth et al., 2010).

This paper describes the diachronous pattern of deformation and metamorphism within the metamorphic hinterland of the northern Cordilleran orogen by reviewing previously published structural, thermobarometric, in situ U-Pb sensitive high-resolution ion microprobe (SHRIMP), K-Ar, and $^{40}Ar/^{39}Ar$ data. From this analysis, it is concluded that the transposition fabrics and the associated amphibolite-facies metamorphism, which is nearly ubiquitous throughout the hinterland, did not develop during a single tectono-metamorphic event. Rather, ductile deformation and amphibolite-facies metamorphism developed diachronously, becoming younger both structurally downward and northeastward (present-day coordinates) toward the foreland. The transitory nature of deformation and metamorphism implies that these processes operate in different places at different times. Therefore, even though we describe a similar transposition foliation, denoted S_T, accompanied by amphibolite-facies metamorphism with similar calculated *P-T* conditions throughout the hinterland, the diachronous nature of these processes strongly suggests that they may not be correlative across the orogen.

We suggest that the diachronous Early Jurassic to mid-Cretaceous tectono-metamorphism may be explained by foreland-directed growth, and underplating beneath a critically tapered orogenic wedge. In this model, rocks in front of the wedge were episodically underthrust downward into a spatially and temporally transient, distributed, amphibolite-facies, transposition-forming shear zone at 25–30 km depth near the base of the overriding wedge. Rocks previously underthrust, buried, and metamorphosed were progressively exhumed to higher structural levels within the wedge, as the upper crust entered a state of extension in order to maintain a critically tapered wedge. This model is akin to a model originally proposed by Platt (1986) and later adapted by Brown (2004) to explain a similar, and in part contemporaneous, diachronous pattern of structurally downward younging ductile deformation in the southeastern Canadian Cordillera.

We also review regional geologic relationships and data that suggest the dynamics within the northern Cordilleran orogen changed considerably during the mid-Cretaceous (ca. 115 Ma), from earlier orogen-normal shortening and associated critical wedge dynamics to lateral (orogen-parallel) extrusion and collapse of the orogenic wedge. A model is presented to account for the mid-Cretaceous synconvergent orogen-parallel–directed extension in west-central Yukon and east-central Alaska. This model is analogous to models presented to explain similar observations in the Himalayas, Turkey, and the eastern Alps.

NORTHERN CORDILLERAN OROGEN

The northern Cordilleran orogen formed as a result of the successive accretion of allochthonous terranes to the western margin of Laurentia, beginning as early as the Late Permian to Early Triassic (Beranek and Mortensen, 2011), persisting through the Mesozoic and Cenozoic, and continuing today (Monger and Price, 2002; Nelson et al., 2013; Staples et al., 2013, 2014). The core of the northern Cordilleran orogen in British Columbia, Yukon, and eastern Alaska consists of an interrelated set of magmatic arcs (Quesnel and Stikine terranes), arcs built on continental fragments (Yukon-Tanana terrane), and an ocean basin (Slide Mountain terrane), collectively referred to as the Intermontane terranes (Monger et al., 1982; Nelson et al., 2013), which were accreted to the western Laurentian margin in Permian–Triassic time (Fig. 1; Colpron et al., 2007; Beranek and Mortensen, 2011). These rocks enclose the Cache Creek terrane—an accretionary complex consisting in part of carbonate bodies that cap seamounts or oceanic plateaus and that contain fauna suggesting that portions of the Cache Creek terrane lay far to the west of the North American continent during the Permian to Middle Triassic (Monger and Ross, 1971; Orchard et al., 2001; Nelson et al., 2013).

In an attempt to explain the present envelopment of the "exotic" Cache Creek terrane, Mihalynuk et al. (1994) proposed that by the late Paleozoic–early Mesozoic, the Quesnel and Stikine terranes were linked to opposite ends of the Yukon-Tanana terrane (cf. Colpron et al., 2007), and that the Stikine and outboard portion of the Yukon-Tanana terrane rotated counterclockwise through the Late Triassic to Early Jurassic, enclosing the Cache Creek terrane to the south. In their model, the northern Yukon-Tanana terrane constitutes the "hinge" of the orocline. The oroclinal bending model of Mihalynuk et al. (1994) remains controversial. If correct, the regional pattern of structurally downward and northeastward younging of deformation and metamorphism presented here spans an area east of the hinge line of the orocline. Therefore, the Yukon-Tanana terrane in the region of this study may have been significantly widened (perhaps as much as doubled), but this occurred largely outboard and prior to the development of the orogenic wedge we present for the Early Jurassic to mid-Cretaceous.

Crustal fragments and magmatic arcs of the Insular terranes (Peninsular, Alexander, and Wrangellia terranes) were subsequently accreted to the outboard margin of the Yukon-Tanana and Stikine terranes (Intermontane terranes) starting in the Early to Middle Jurassic (McClelland and Gehrels, 1990; McClelland et al., 1992; van der Heyden, 1992; Saleeby, 2000; Gehrels, 2001). In the southern Canadian Cordillera, the accretion of these two composite terranes and associated crustal thickening resulted in two major metamorphic belts separated by a zone of low-grade, weakly deformed rocks of the Quesnel, Cache Creek, and Stikine terranes (Monger et al., 1982). By contrast, in the northern Cordillera, in west-central Yukon and east-central Alaska, amphibolite-facies metamorphism is laterally continuous across the Yukon-Tanana terrane west of North American margin sedimentary rocks all the way to the Denali fault (Fig. 1). Accretion of the Insular terranes against the Yukon-Tanana terrane may have resulted in complex overprinting and reworking of earlier deformation and metamorphism within the growing northern Cordilleran hinterland.

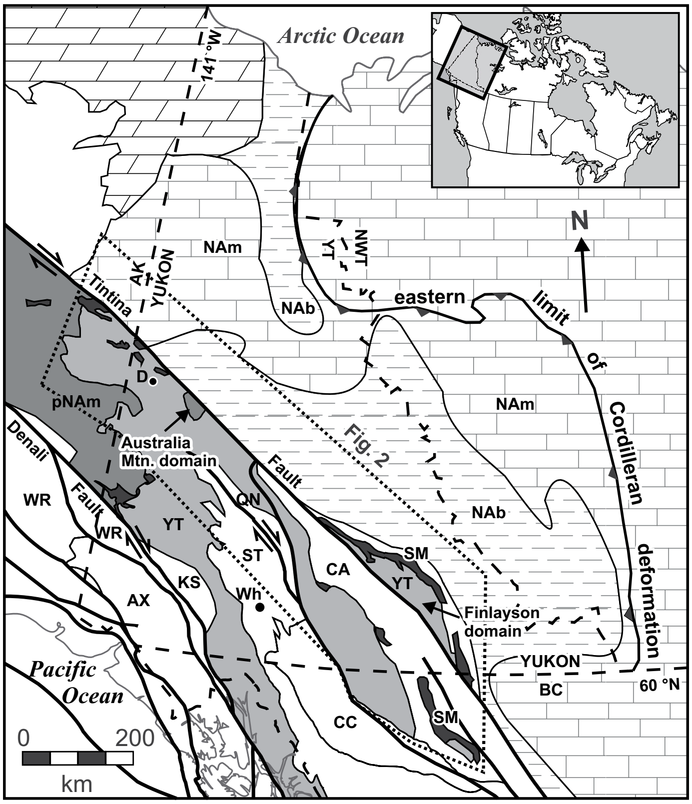

Figure 1. Simplified terrane map of the northern Canadian Cordillera (modified from Colpron et al., 2006) showing location of Figure 2. Note, much of Yukon-Tanana terrane southwest of the Tintina fault is at amphibolite facies (cf. Read et al., 1991). Cities: D—Dawson; Wh—Whitehorse. Terrane abbreviations: AX—Alexander; CA—Cassiar; CC—Cache Creek; KS—Kluane Schist; NAb—North American basinal strata; NAm—North American platformal strata; pNAm—parautochthonous North American continental margin; QN—Quesnellia; SM—Slide Mountain; ST—Stikinia; YT—Yukon-Tanana; WR—Wrangellia. Political divisions: AK—Alaska; NWT—Northwest Territories; BC—British Columbia.

The along-strike paleogeographic setting of the Yukon-Tanana terrane relative to the Insular terranes is uncertain due to post–Early Cretaceous dextral displacement along the Tintina and Denali faults (Gabrielse et al., 2006; Dodds, 1995), as well as Late Jurassic to Early Cretaceous sinistral motion of the Insular terranes (Monger et al., 1994). The Kahiltna, Nutzotin, and Gravina basins form a discontinuous belt of Late Jurassic–Cretaceous marine sediments (±volcanic and volcaniclastic rocks), spanning from south-central Alaska to northwestern British Columbia, between the Insular terranes and the Intermontane terranes. These basins have been variously interpreted to have formed prior to accretion of the Insular terranes, during accretion, and as a transtensional basin following terrane accretion (Coney et al., 1980; Monger et al., 1982, 1994; Kapp and Gehrels, 1998; Ridgway et al., 2002; Kalbas et al., 2007; Trop and Ridgway, 2007; Gehrels et al., 2009; Hampton et al., 2010). Furthermore, estimates for the timing of accretion along different parts of the Insular-Intermontane boundary range from Middle Jurassic to Late Cretaceous (McClelland and Gehrels, 1990; McClelland et al., 1992; van der Heyden, 1992; Saleeby, 2000; Gehrels, 2001; Ridgway et al., 2002; Trop and Ridgway, 2007; Hampton et al., 2010; Hults et al., 2013), suggesting an oblique collision initiating in the south and becoming younger to the northwest.

Herein, we focus on the tectono-metamorphic history of the north-central and northeastern portions of Yukon-Tanana terrane and the structurally underlying parautochthonous continental margin rocks (outlined in Fig. 2), which record both the early accretionary history of the peri-Laurentian terranes with western Laurentia, as well as events coeval with the subsequent accretion of the Insular terranes. The northeast portion of the Yukon-Tanana terrane (Finlayson Lake district) is interpreted to have been offset ~490 km to the southeast through a combined 430 km of dextral strike-slip displacement along the Tintina fault in the Paleogene, and ~60 km of extension in the Cretaceous (Roddick, 1967; Dover, 1994; Gabrielse et al., 2006). Figures 2, 3, and 4 show the restored position of this offset block of the Yukon-Tanana terrane (Finlayson Lake district) relative to its counterpart to the west, and they provide the framework for the following discussion.

TERRANE NOMENCLATURE

The Yukon-Tanana terrane consists of a pre–Late Devonian metasedimentary basement (Snowcap assemblage) with lithological, geochemical, and isotopic compositions that suggest it represents a rifted portion of the western Laurentian continental margin (Piercey and Colpron, 2009; Colpron and Nelson, 2009). The Snowcap assemblage is overlain by three unconformity-bounded Upper Devonian to Permian volcanic arc sequences (Finlayson, Klinkit, Klondike assemblages) that are coeval with oceanic chert, argillite, and mafic volcanic rocks of the Slide Mountain terrane (Colpron et al., 2006, 2007). The Slide Mountain terrane represents the preserved remnants of a Late Devonian to Permian back-arc ocean basin that opened between the continental margin and the Late Devonian–Permian arcs of the Yukon-Tanana terrane (Nelson et al., 2006).

Ductilely deformed, amphibolite-facies rocks in east-central Alaska, previously mapped as allochthonous rocks of the Yukon-Tanana terrane, have recently been reinterpreted as parautochthonous North American continental margin rocks (Lake George and Totatlanika assemblages in Fig. 2) exhumed from beneath the Yukon-Tanana terrane along mylonitic extensional faults in the mid-Cretaceous (Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2002, 2006). A parautochthonous North American origin for these rocks in east-central Alaska is based on Archean and Proterozoic U-Pb zircon inheritance and detrital ages, stratigraphic similarity with rocks in the Selwyn Basin, their structural position, and a lack of late Paleozoic (post–ca. 357 Ma) arc assemblages, which are characteristic of the Yukon-Tanana terrane (Dusel-Bacon et al., 2006; Nelson et al., 2006; Dusel-Bacon and Williams, 2009), but which are largely absent from the North American margin (Nelson et al., 2006). Similar characteristics, including the following list of observations and data, lead us to interpret a small domain (Australia Mountain domain; Figs. 3 and 4; Staples et al., 2013) in west-central Yukon to also represent parautochthonous North American continental margin rocks: (1) apparent lack of post–early Mississippian (ca. 357 Ma) Paleozoic arc assemblages characteristic of the Yukon-Tanana terrane (Nelson et al., 2006), (2) apparent absence of Permian–Triassic and Early Jurassic regional metamorphism documented in adjacent portions of the Yukon-Tanana terrane southwest of the Tintina fault (Berman et al., 2007; Staples et al., 2013; Staples, 2014), (3) absence of Early to Middle Jurassic $^{40}Ar/^{39}Ar$ and K-Ar cooling ages prevalent throughout the Yukon-Tanana terrane southwest of the Tintina fault (Staples, 2014), and (4) exhumation of moderate- to high-pressure amphibolite-facies rocks in the Australia Mountain domain from beneath the Yukon-Tanana terrane along mid-Cretaceous extensional shear zones (Staples et al., 2013), similar to the parautochthonous rocks in east-central Alaska noted earlier. Note, each of the preceding points is not conclusive on their own, and given the limited data, we cannot determine definitively whether the Australia Mountain domain is Yukon-Tanana arc substrate (e.g., Snowcap assemblage) or parautochthonous North American continental margin rock. However, we feel that, collectively, the data and observations from these rocks share more characteristics with parautochthonous North American rocks in east-central Alaska than Yukon-Tanana terrane, and they are thus herein interpreted as parautochthonous North America continental margin rocks.

Collectively, these allochthonous and parautochthonous rocks of the Yukon-Tanana terrane and North American continental margin, respectively, record a protracted and diachronous history of ductile deformation and amphibolite-facies metamorphism associated with terrane accretion and subsequent crustal thickening (Dusel-Bacon et al., 1995; Berman et al., 2007; Beranek and Mortensen, 2011; Staples et al., 2013, 2014).

SPATIAL AND TEMPORAL RECORD OF DIACHRONOUS AMPHIBOLITE-FACIES METAMORPHISM AND DUCTILE DEFORMATION

Highly deformed and transposed amphibolite-facies rocks of the pericratonic Yukon-Tanana terrane and the structurally underlying parautochthonous North American continental margin are exposed across a wide area (at least 100,000 km^2) within the metamorphic core of the northern Cordilleran orogen in west-central Yukon and east-central Alaska (Figs. 1 and 4). These amphibolite-facies rocks share a similar style and pattern of deformation characterized by the transposition of lithologic contacts and primary compositional layering into a regional ductile foliation (S_T) with at least one generation of intrafolial isoclinal folds (Foster et al., 1985, 1994; Colpron, 1999, 2005; de Keijzer et al., 1999; Gallagher, 1999; Gordey and Ryan, 2005; Berman et al., 2007; Staples et al., 2013, 2014). Petrology and phase equilibria modeling (Dusel-Bacon et al., 1995; Berman et al., 2007; Staples et al., 2013, 2014) indicate these rocks were ductilely deformed and metamorphosed under nearly identical conditions at 7.5–9 kbar and 600–680 °C. However, monazite growth associated with this deformation and metamorphism was strongly diachronous across the orogen, with events recorded in the latest Middle Permian–Middle Triassic, Early Jurassic, Middle Jurassic to Early Cretaceous, and Early to mid-Cetaceous (Berman et al., 2007; Staples, 2014; Staples et al., 2013, 2014). Each of these tectono-metamorphic events is recorded in distinct domains and typically lacks evidence of the older or younger events recorded in the other domains (Fig. 4). Both the Permian–Triassic and Early Jurassic metamorphic events are recorded in Yukon-Tanana terrane rocks within the Stewart River map area southwest of the Tintina fault (Berman et al., 2007). Rocks deformed and metamorphosed in the Permian–Triassic and Early Jurassic were exhumed in the Early Jurassic (Dusel-Bacon et al., 2002; Berman et al., 2007). By contrast, rocks farther to the east were progressively buried and heated from Middle Jurassic to Early Cretaceous time in the Finlayson domain (Staples et al., 2014), and in the Early to mid-Cretaceous in the Australia Mountain domain (Fig. 4; Staples et al., 2013). Figure 5 shows a schematic cross-sectional view that cuts through each of these three tectono-metamorphic domains. A fourth domain of weakly deformed and essentially unmetamorphosed rocks with Late Devonian to Mississippian cooling ages (Knight et al., 2013) is juxtaposed to the southeast in the hanging wall of mid-Cretaceous normal faults (Fig. 4).

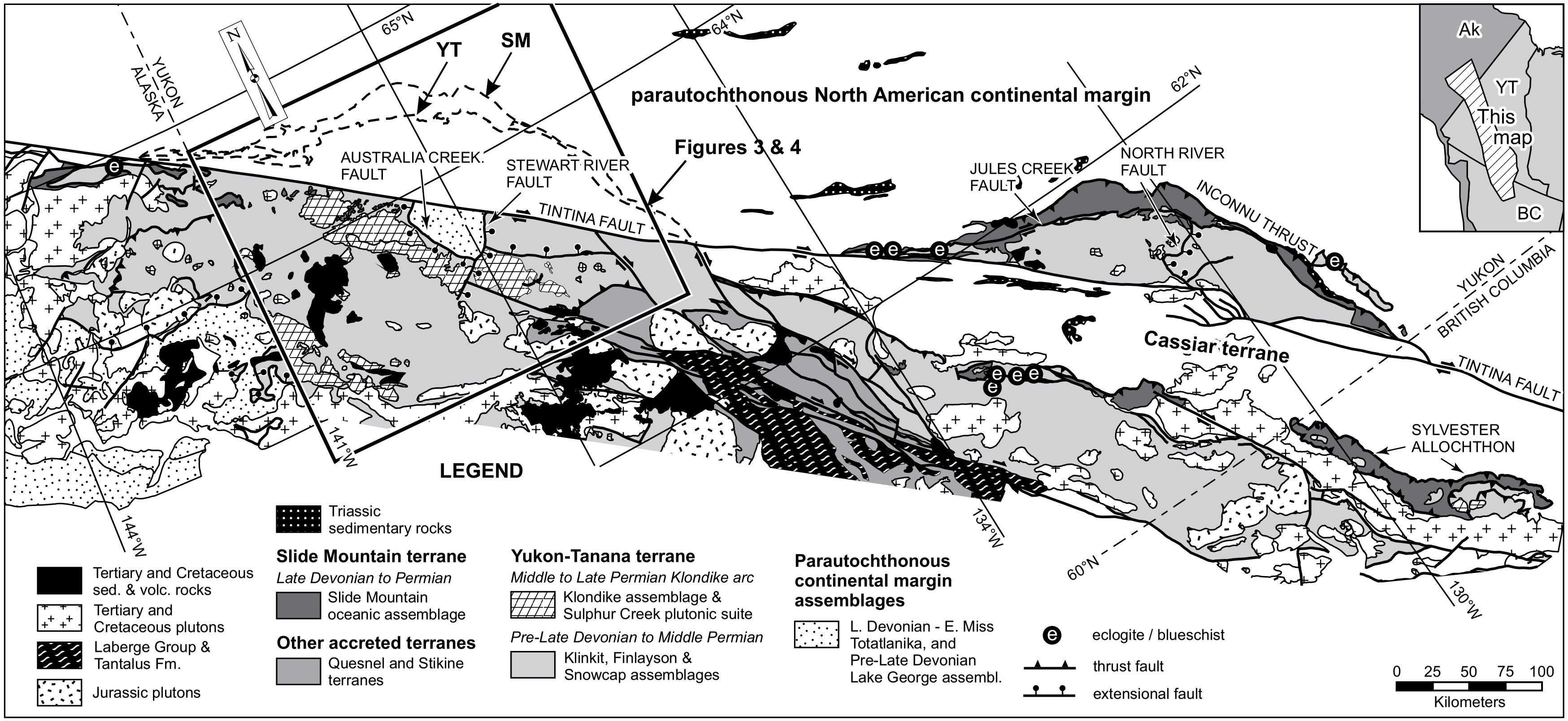

Figure 2. Tectonic assemblage map of Yukon-Tanana and adjacent terranes of the northern Cordillera in east-central Alaska (Ak), central Yukon (YT), and northern British Columbia (BC). The location of Figures 3 and 4 is outlined by a thick black square. Dashed outlines labeled SM and YT show the original position of the Slide Mountain and Yukon-Tanana terranes now located within the Finlayson Lake area, prior to offset along the Tintina fault (Gabrielse et al., 2006). Figure is modified from Colpron et al. (2006).

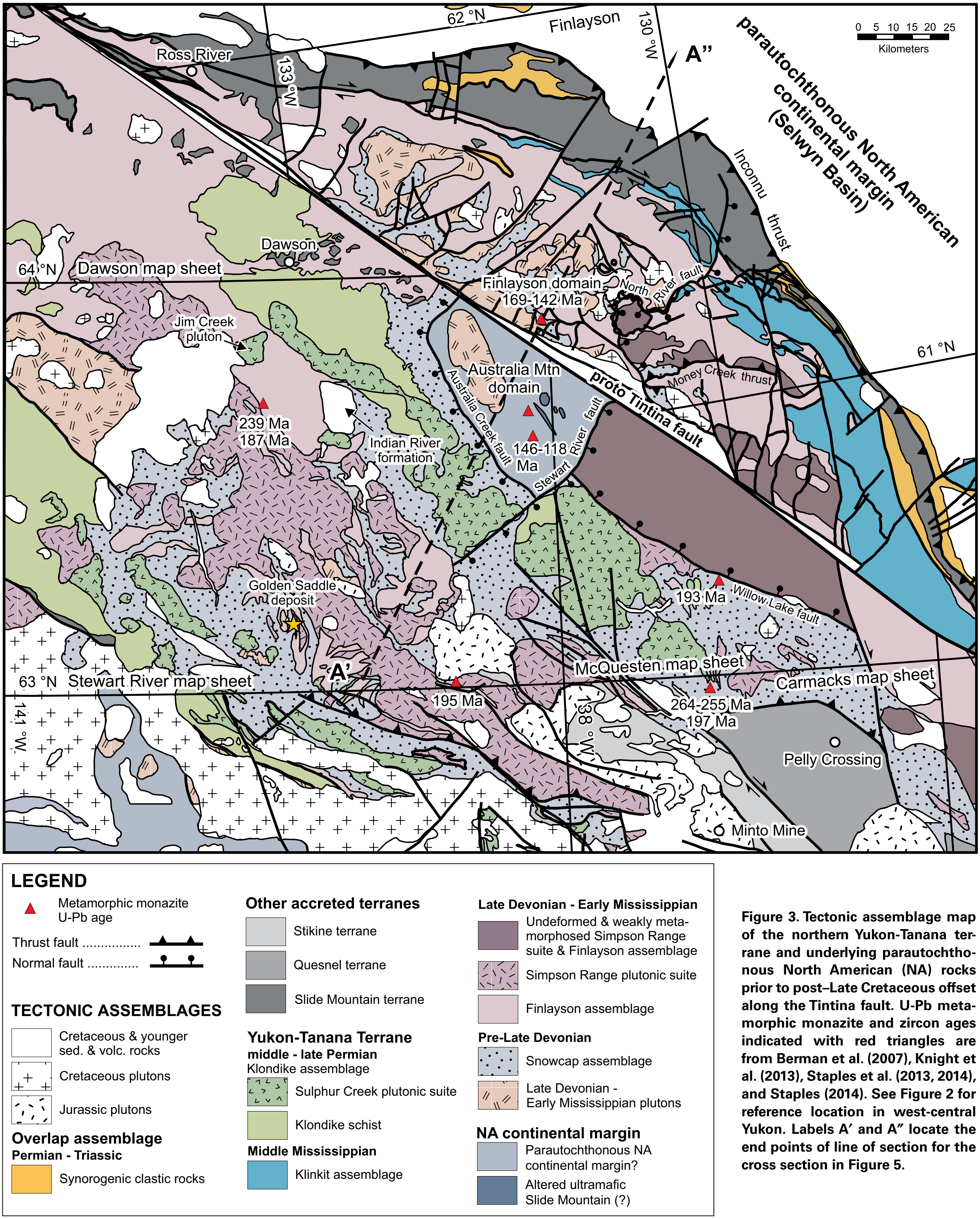

Figure 3. Tectonic assemblage map of the northern Yukon-Tanana terrane and underlying parautochthonous North American (NA) rocks prior to post–Late Cretaceous offset along the Tintina fault. U-Pb metamorphic monazite and zircon ages indicated with red triangles are from Berman et al. (2007), Knight et al. (2013), Staples et al. (2013, 2014), and Staples (2014). See Figure 2 for reference location in west-central Yukon. Labels A′ and A″ locate the end points of line of section for the cross section in Figure 5.

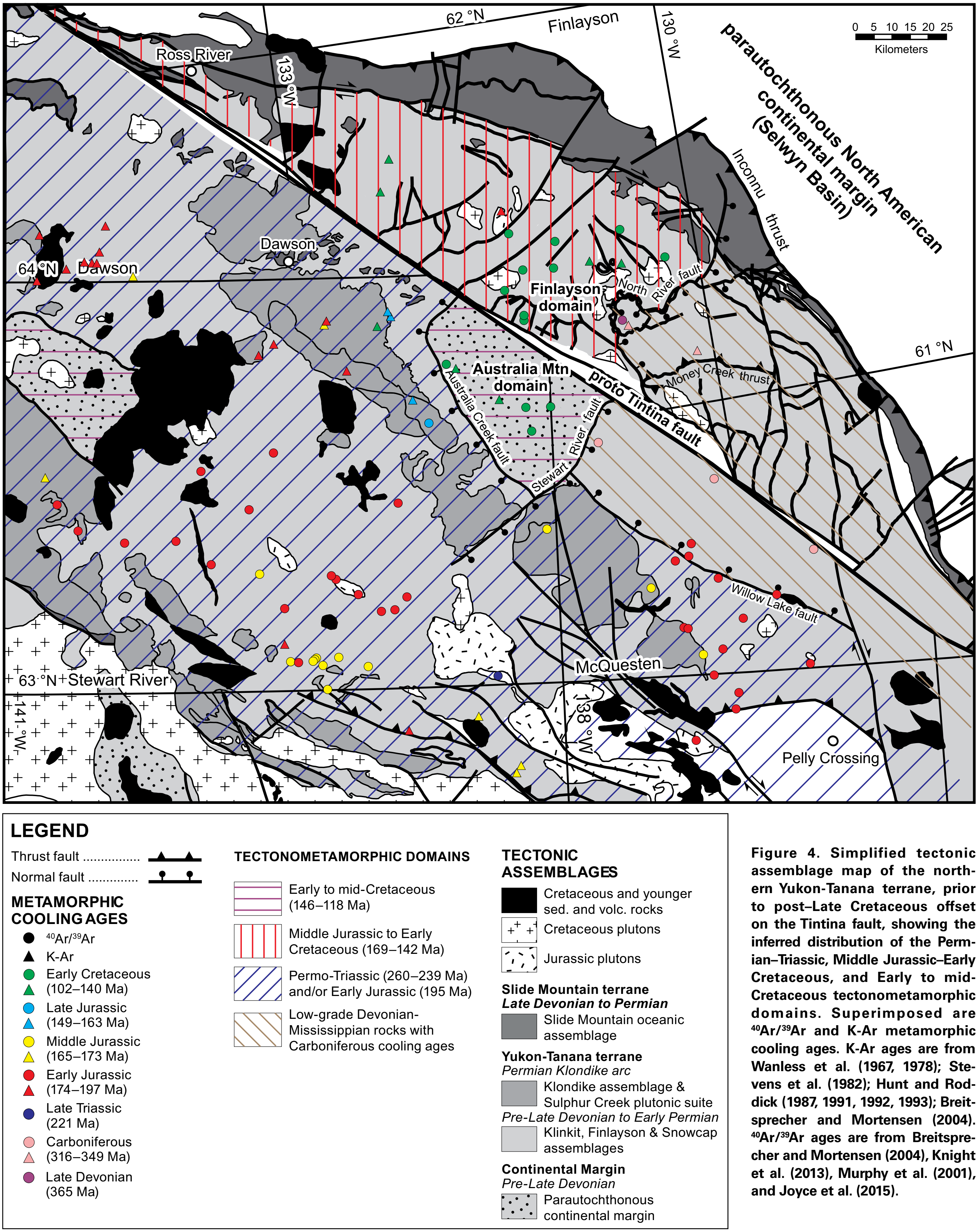

Figure 4. Simplified tectonic assemblage map of the northern Yukon-Tanana terrane, prior to post–Late Cretaceous offset on the Tintina fault, showing the inferred distribution of the Permian–Triassic, Middle Jurassic–Early Cretaceous, and Early to mid-Cretaceous tectonometamorphic domains. Superimposed are ^{40}Ar/^{39}Ar and K-Ar metamorphic cooling ages. K-Ar ages are from Wanless et al. (1967, 1978); Stevens et al. (1982); Hunt and Roddick (1987, 1991, 1992, 1993); Breitsprecher and Mortensen (2004). ^{40}Ar/^{39}Ar ages are from Breitsprecher and Mortensen (2004), Knight et al. (2013), Murphy et al. (2001), and Joyce et al. (2015).

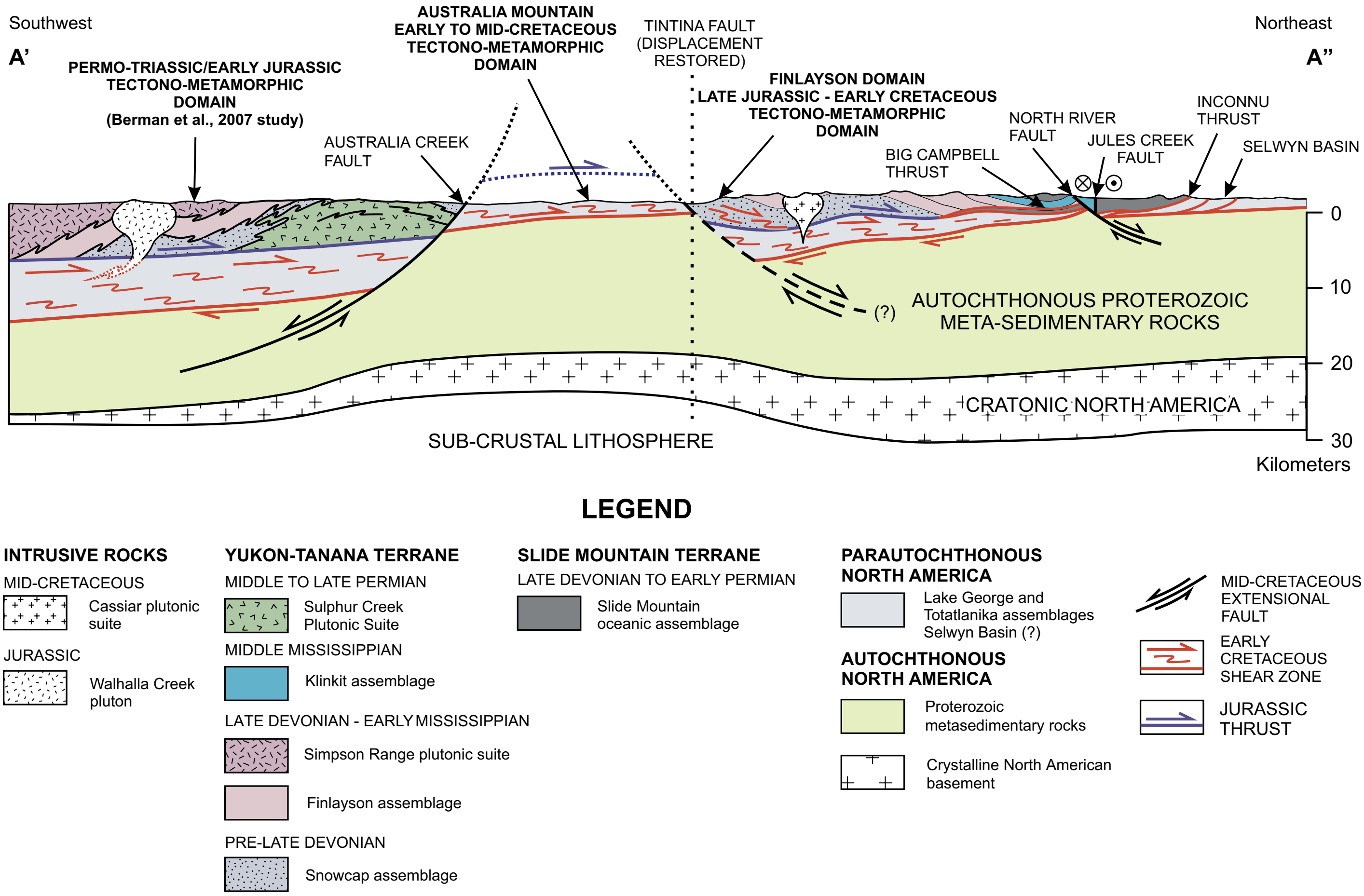

Figure 5. Schematic cross section (A′–A″ on Fig. 3) through all three of the temporally distinct tectono-metamorphic domains: Permian–Triassic (Early Jurassic) domain (Berman et al., 2007); Early to mid-Cretaceous domain (Australia Mountain domain; Staples et al., 2013); and Middle Jurassic–Early Cretaceous domain (Finlayson domain; Staples et al., 2014). This cross section also illustrates the downward migration of the Early Cretaceous shear zone (in red) relative to the Jurassic shear zone (in blue). The dashed normal fault coinciding with the proto–Tintina fault is inferred as one possible explanation for the 5 km of structural relief between the Australia Mountain (9 kbar metamorphism) and Finlayson (7.5 kbar metamorphism) domains. Presence and approximate thickness of lithologic units are constrained by thermobarometric data (Staples et al., 2013) and the interpretation of Lithoprobe seismic-reflection profiles of Cook et al. (2004), who interpreted an equivalent thickness of the Selwyn Basin (parautochthonous North American [NA] rocks) beneath the Yukon-Tanana terrane. No vertical exaggeration.

Permian–Triassic Tectono-Metamorphic Domain—North-Central Yukon-Tanana Terrane, West-Central Yukon

Permian–Triassic

Timing estimates for the development of a regional transposition foliation (S_T) and associated amphibolite-facies metamorphism in the north-central portion of the Yukon-Tanana terrane in west-central Yukon range from latest Middle Permian (ca. 264–253 Ma; Berman et al., 2007; Beranek and Mortensen, 2011; Staples, 2014) to Middle Triassic (ca. 239 Ma; Berman et al., 2007). Staples (2014) obtained U-Pb ages of 263.6 ± 3.4 Ma and 254.7 ± 2.6 Ma from single SHRIMP spots on a monazite included in garnet and the Y-rich core of a matrix monazite grain, respectively, within a garnet-muscovite-biotite schist of the Snowcap assemblage in the northern Carmacks map area (Fig. 3). In the Stewart River map area, Beranek and Mortensen (2011) obtained a ca. 259 Ma U-Pb zircon age from a “strongly foliated” quartz monzonite sill. They interpreted this sill to have been affected by the same ductile deformation that produced the regional foliation (S_T) at lower amphibolite facies within the host Devonian–Mississippian Finlayson assemblage of the Yukon-Tanana terrane. If this interpretation is correct, then the ca. 259 Ma age from the deformed sill provides a maximum age for the development of the regional ductile deformation. However, if the regional foliation in the country rock (Finlayson assemblage) is not the same as that in the ca. 259 Ma sill, it may be possible that the regional foliation is older (e.g., Devonian–Mississippian). In the same area, the little-deformed Jim Creek pluton (Fig. 3) and associated dikes cut transposed Nasina assemblage rocks and yield an age of ca. 253 Ma (Beranek and Mortensen, 2011), suggesting that distributed, penetrative deformation had ceased by this time. However, only ~10 km to the south (Fig. 3), Berman et al. (2007) dated ca. 239 Ma monazite included in garnet rims grown in pressure shadows that parallel the transposition foliation. These monazite are linked to an ~9 kbar and 600 °C metamorphic event responsible for the garnet overgrowths (Berman et al., 2007), indicating that ductile deformation at amphibolite-facies conditions continued until the Middle Triassic, somewhat younger than the presently known duration of plutonism between ca. 260 and 253 Ma.

Permian–Triassic metamorphism (ca. 260–240 Ma; Berman et al., 2007) in the north-central portion of the Yukon-Tanana terrane is spatially and temporally associated with a belt of Permian (ca. 265–253 Ma) magmatic rocks (Klondike assemblage; Mortensen, 1990; Gordey and Ryan, 2005; Ruks et al., 2006). Figure 4 shows the distribution of plutonic and volcanic rocks of the Permian Klondike assemblage and the inferred distribution of Permian–Triassic (ca. 260–240 Ma; Berman et al., 2007) amphibolite-facies metamorphism. The Middle to Late Permian Klondike assemblage and a discontinuous belt of Early to Middle Permian (ca. 273–260 Ma) blueschist and eclogite to the northeast, locally occurring along the eastern side of the Yukon-Tanana terrane (Figs. 2 and 3; Creaser et al., 1997; Erdmer et al., 1998), are interpreted to record a Permian northeast-facing magmatic arc and accretionary wedge, respectively (Fig. 6; Mortensen, 1992; Nelson et al., 2006).

By Middle Triassic time, siliciclastic strata that contain detrital zircon sourced from the Paleozoic arc assemblages of the Yukon-Tanana terrane were deposited on the ancestral North American continental margin (Beranek et al., 2010; Beranek and Mortensen, 2011). This depositional relationship implies that the Slide Mountain ocean had largely closed by the Early Triassic, and the Yukon-Tanana terrane had been accreted and uplifted, forming a highland that shed detritus into the depocenter of the western Laurentian margin at this time (Fig. 6A). Beranek and Mortensen (2011) suggested that the Late Permian tectono-metamorphism was therefore the result of the accretion of the Yukon-Tanana terrane onto the western Laurentian margin. The presence of ca. 239 Ma monazite linked to 600 °C and ~9 kbar metamorphism and ductile deformation (Berman et al., 2007) suggests this event continued into the Middle Triassic.

Map relationships in the northern Carmacks area suggest that Late Triassic volcanic rocks (Stikine terrane; Fig. 3) directly overlie basement rocks of the Yukon-Tanana terrane (Ryan et al., 2010), thus suggesting exhumation of this portion of the Yukon-Tanana terrane by Late Triassic time. However, the possibility of a structural contact cannot be ruled out because of poor exposure.

Early Jurassic

An Early Jurassic (ca. 197–187 Ma) metamorphic overprint is documented locally within the Permian–Triassic tectono-metamorphic domain (Berman et al., 2007; Knight et al., 2013; Staples, 2014). The oldest Early Jurassic metamorphic age of ca. 197 Ma comes from the northern Carmacks map area (Fig. 3) and was obtained from a single SHRIMP spot on the low-Y rim of the same matrix monazite grain that yielded the ca. 255 Ma age from the Y-rich core (Staples, 2014). Berman et al. (2007) linked a ca. 195 Ma U-Pb monazite age in staurolite- and kyanite-bearing rocks in the southern portion of the Stewart River map area to metamorphic conditions of 600 °C and ~7.6 kbar. Additionally, Knight et al. (2013) obtained an Early Jurassic U-Pb age (ca. 193 Ma) from low-Th/U zircon rims, which they interpreted as metamorphic overgrowths, within a ca. 322 Ma metafelsite in the McQuesten map area. Slightly younger, ca. 187 Ma, Y-rich monazite in the Stewart River map area, was interpreted by Berman et al. (2007) to have grown during retrograde resorption of garnet.

The regional extent of Early Jurassic metamorphism remains unclear. However, contrary to the Permian–Triassic, Early Jurassic metamorphism does not appear to have been accompanied by distributed, penetrative fabric development. This is based on the presence of randomly oriented Early Jurassic kyanite crystals and Early Jurassic intrusions that crosscut the regional penetrative transposition foliation (Berman et al., 2007). Therefore, the penetrative transposition foliation and associated amphibolite-facies mineral assemblages throughout a widespread area of the Stewart River map area appear to be of latest Middle Permian to Middle Triassic age, as noted already.

Late Triassic–Early Jurassic granitic plutons intrude the Yukon-Tanana, Quesnel, and Stikine terranes. Al-in-hornblende geobarometric estimates (4–7 kbar; McCausland et al., 2002; Tafti, 2005) and U-Pb zircon ages (Tafti, 2005; Hood, 2012; Knight et al., 2013) indicate emplacement at moderate depths (13–23 km assuming 1 kbar ≈ 3.3 km) between 205 and 197 Ma, prior to, and possibly synchronous with, the Early Jurassic (ca. 195 Ma) metamorphic overprint. These Early Jurassic plutons may have provided fluids to act as a catalyst for the Early Jurassic metamorphic overprint; however, thermobarometric estimates of 600 °C and ~7.6 kbar (Berman et al., 2007) indicate these rocks were deep in the crust (~25 km depth) in the Early Jurassic, and this was thus not simply a contact metamorphic event. Altogether, these data indicate that the Permian–Triassic tectono-metamorphic domain was reburied to midcrustal levels in the Early Jurassic following exhumation and extrusion of volcanics in the Late Triassic. Alternatively, portions of the Permian–Triassic domain may have remained at depth into the Early Jurassic.

Early to Middle Jurassic (ca. 197–171 Ma) K-Ar and $^{40}Ar/^{39}Ar$ hornblende and mica cooling ages throughout this region of the Yukon-Tanana terrane (Fig. 4; Wanless et al., 1978; Hunt and Roddick, 1991, 1992; Breitsprecher and Mortensen, 2004; Knight et al., 2013; Joyce et al., 2015) overlap with Early Jurassic U-Pb metamorphic monazite and zircon ages and immediately postdate Early Jurassic pluton crystallization ages. These age relationships suggest that a large part of the Permian–Triassic metamorphic domain was exhumed to upper-crustal levels synchronous with, or very rapidly after, plutonism and metamorphic overprinting in the Early Jurassic. Exhumation of the Permian–Triassic domain was accommodated in part by extension along the Willow Lake normal fault (Fig. 4), which bounds a portion of the Permian–Triassic domain and preserves rocks exhumed in the Carboniferous in its hanging wall (Colpron and Ryan, 2010; Knight et al., 2013). The preservation of Early Jurassic K-Ar and $^{40}Ar/^{39}Ar$ mica cooling ages within the Permian–Triassic metamorphic domain reveals that this domain was unaffected by younger Middle Jurassic to Early Cretaceous and Early to mid-Cretaceous metamorphic events recorded in structurally lower levels now presently exposed to the northeast (Fig. 4; Finlayson and Australia Mountain domains, respectively).

Middle Jurassic to Early Cretaceous Tectono-Metamorphic Domain—Finlayson Domain, Northeastern Yukon-Tanana Terrane

After restoration of the Tintina fault, the offset portion of the Yukon-Tanana terrane in the Finlayson domain restores to the northeast of the Permian–Triassic tectono-metamorphic domain in western Yukon (Figs. 2, 3, and 4). The Finlayson domain is bound to the southeast by the North River fault, a regional-scale mid-Cretaceous normal fault that cuts across the Yukon-Tanana terrane in a roughly northeast-southwest trend (Figs. 3 and 4; Murphy, 2004). Rocks of the Finlayson domain in the footwall record mid-Cretaceous $^{40}Ar/^{39}Ar$ and K-Ar cooling ages (Fig. 4; Wanless et al., 1967; Hunt and Roddick, 1992; Murphy et al., 2001; Joyce et al., 2015), are intruded by mid-Cretaceous granitoid plutons (Murphy et al., 2001), and have been ductilely deformed at amphibolite facies prior to their intrusion (Murphy, 2004; Staples et al., 2014). Staples et al. (2014) showed that rocks in the footwall of the North River fault experienced a protracted episode of monazite growth from ca. 169 to 142 Ma coeval with the development of ductile transposition fabrics and garnet growth from ~550 °C and 6.5 kbar to 600 °C and 7.5 kbar. In contrast, subgreenschist- to greenschist-facies rocks in the hanging wall to the southeast constitute the upper thrust sheets of the imbricated Yukon-Tanana terrane that lack Cretaceous plutons and contain Mississippian and Pennsylvanian K-Ar cooling ages and a latest Devonian $^{40}Ar/^{39}Ar$ cooling age (Fig. 4; Stevens et al., 1982; Hunt and Roddick, 1987; Joyce et al., 2015).

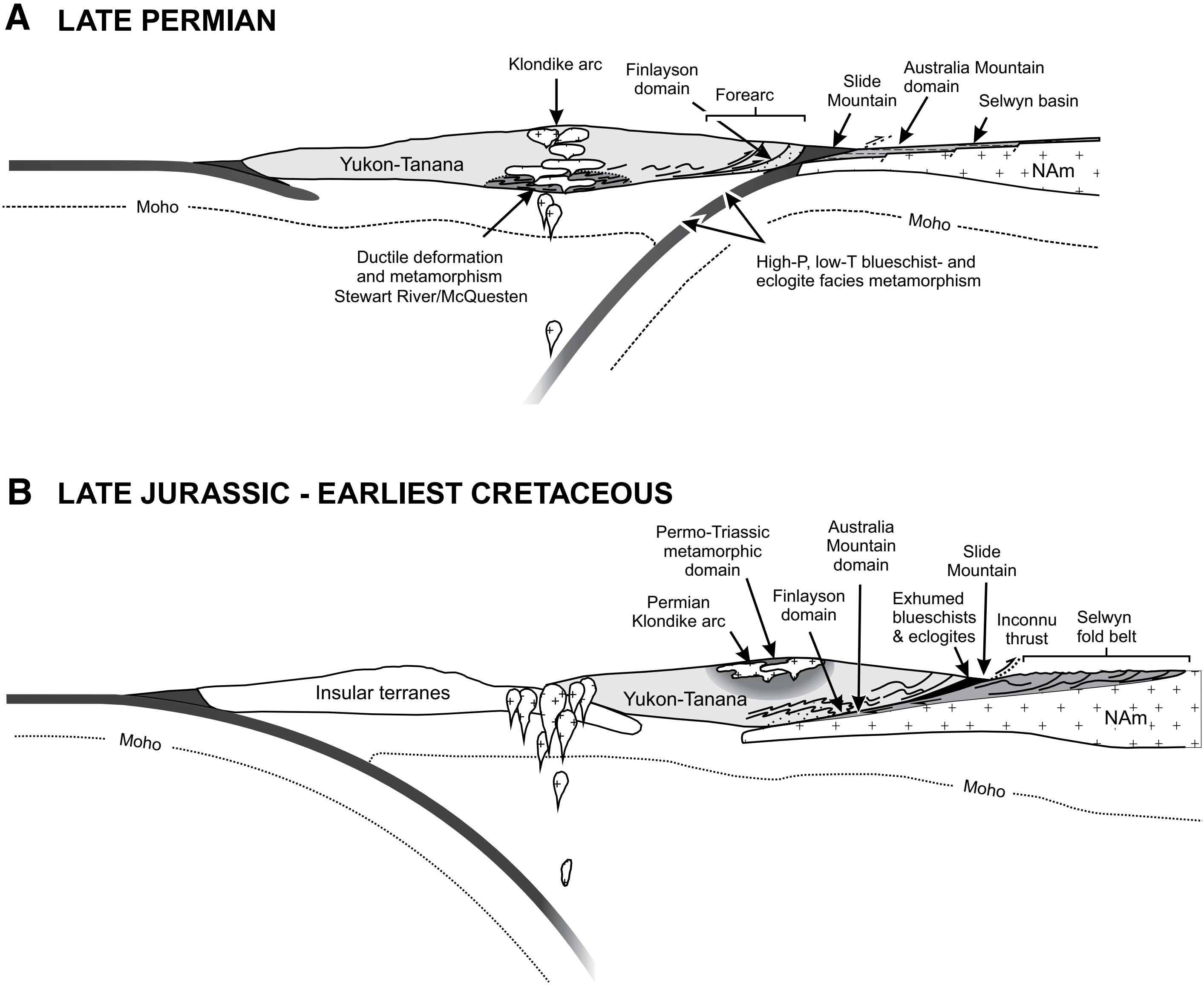

Figure 6. Schematic crustal sections (not drawn to scale) of the northern Cordilleran margin showing the interpreted crustal position of the metamorphic domains before and during Mesozoic deformation and metamorphism of the Yukon-Tanana terrane. (A) In Late Permian, the Finlayson domain was located in the forearc region with respect to the Klondike domain. The Australia Mountain domain is inferred to have originated in distal extension of the ancestral North American (NAm) margin prior to underthrusting beneath the Yukon-Tanana terrane. This time frame postdates extreme thinning of the Yukon-Tanana terrane in the latest Middle Permian (Johnston et al., 2007). (B) Late Jurassic–Early Cretaceous (ca. 169–142 Ma), prior to Paleogene offset along the Tintina fault and mid-Cretaceous extension within the Yukon-Tanana terrane, and after the westward underthrusting of the Yukon-Tanana terrane that produced the deformation and metamorphism recorded in the Finlayson Lake district, and initial shortening in the Selwyn fold belt. At that time, the Australia Mountain domain is inferred to have begun westward underthrusting beneath the Yukon-Tanana terrane en route to peak metamorphism of 9 kbar at ca. 146–118 Ma (Staples et al., 2013). Figure is modified from Staples et al. (2014).

There is no record of Permian–Triassic tectono-metamorphism in the Finlayson domain. It is possible that evidence of this event, for example, recorded by the growth of a metamorphic thermochronometer such as monazite, may have been destroyed by the low-temperature dissolution of such minerals (e.g., Williams et al., 2011). Alternatively, it is more likely that monazite growth was a function of location within the thermal structure of the terrane in the Permian–Triassic. The Permian–Triassic amphibolite-facies metamorphism in west-central Yukon was coincident and spatially associated with the Middle to Late Permian (265–253 Ma) Klondike assemblage (Fig. 4; Berman et al., 2007; Nelson et al., 2006; Mortensen, 1992). The absence of a Permian metamorphic signature and the position of Yukon-Tanana terrane assemblages in the Finlayson domain northeast of the Klondike arc-center and west of high-*P-T* subduction complex eclogites suggest it occupied a position in the cooler, stronger forearc region of a Middle to Late Permian northeast-facing convergent margin (Fig. 6A; Staples et al., 2014).

Early to Mid-Cretaceous Tectono-Metamorphic Domain—Australia Mountain Domain, Northeastern Stewart River Map Area

Building on the work of Berman et al. (2007), Staples et al. (2013) identified an Early to mid-Cretaceous (ca. 146–118 Ma) syn- to post-S_T amphibolite-facies (9 kbar and 650 °C) metamorphic domain at Australia Mountain, immediately east of the Permian–Triassic tectono-metamorphic domain (Fig. 4). Slightly younger (ca. 112 Ma) texturally and chemically distinct monazites within resorbed portions of garnet from Australia Mountain record the onset of near-isothermal decompression in the mid-Cretaceous following the peak of metamorphism. The massive and discordant mid-Cretaceous (ca. 114–110 Ma) granites found in the tectono-metamorphic domains to the west and east have not been mapped in the Australia Mountain domain. If similar-age plutons are present beneath the surface, they would postdate metamorphism in this domain and thus cannot be responsible for the diachronous metamorphism.

There is no record of Permian–Triassic or Early Jurassic metamorphism and deformation in the Australia Mountain domain. However, synkinematic garnet cores from Australia Mountain, with incipient stages of garnet growth recorded at ~600 °C and 8 kbar, remain undated. Potential metamorphic events responsible for this garnet growth include the Permian–Triassic, Early Jurassic, Middle Jurassic to Early Cretaceous, and Early Cretaceous events, all of which are recorded regionally. We interpret the lack of a Permian metamorphic signature in the Australia Mountain domain to indicate that this parautochthonous domain (Staples et al., 2013, 2014) would have lain east of the Permian subduction zone on the impinging western Laurentian margin and thus well inboard (cratonward) of the orogenic front in the Permian (Fig. 6A).

The abrupt juxtaposition of the Early to mid-Cretaceous Australia Mountain domain against rocks with Jurassic cooling ages to the west and south (Fig. 4; Hunt and Roddick, 1992; Knight et al., 2013), and Paleozoic and Early to Middle Jurassic cooling ages to the southeast (Fig. 4; Knight et al., 2013), suggests that this domain is bounded by two crustal-scale mid-Cretaceous normal faults: the Australia Creek and Stewart River faults, respectively (Figs. 3 and 4; Staples et al., 2013). Poor exposure in the area has prevented the direct observation of faults bounding this Early to mid-Cretaceous tectono-metamorphic domain. The positions of these two faults are constrained by an abrupt change in mica cooling ages (Staples, 2014; Joyce et al., 2015), the presence of distinct discontinuities in aeromagnetic data (Hayward et al., 2012), and differences in lithologies (Gordey and Ryan, 2005; Staples et al., 2013).

After restoration of the Tintina fault, the trace of the North River fault restores along trend of the mid-Cretaceous Stewart River fault west of the Tintina fault (Figs. 3 and 4). Both the North River and Stewart River faults juxtapose rocks ductilely deformed and metamorphosed in the Early to mid-Cretaceous against rocks to the southeast that are generally undeformed and weakly metamorphosed rocks with Mississippian cooling ages (Figs. 3 and 4; Murphy et al., 2001; Murphy, 2004; Staples et al., 2013, 2014; Colpron and Ryan, 2010; Knight et al., 2013). Therefore, prior to Paleogene offset along the Tintina fault, the Stewart River and North River faults likely formed a continuous normal fault. Both the Permian–Triassic and Early Jurassic metamorphic domain to the west and the Devonian–Mississippian rocks to the south were presumably the suprastructural "lid" from beneath which the Jurassic–Cretaceous metamorphic domains were exhumed along the mid-Cretaceous Australia Creek and Stewart River–North River faults, respectively.

EXPLANATION OF DIACHRONOUS DEFORMATION AND METAMORPHISM IN TERMS OF A CRITICAL WEDGE MODEL

Thermal modeling of England and Thompson (1984) illustrates that following a single episode of tectonic thickening, wherein radiogenic heat production is the dominant mode of heating, the isotherms will relax downwards. When coupled with erosion, upper-crustal levels will begin to cool while heating continues at depth. In this model, deformation is experienced simultaneously at each crustal level, but with peak metamorphic temperatures attained at progressively younger times with increasing depth.

However, this model cannot reconcile the development of the metamorphic domains of our study, especially when considering the Early Jurassic and Middle Jurassic to Early Cretaceous events for the following reasons: (1) Both of these events occurred at approximately the same crustal level (7.6 and 7.5 kbar, respectively; Berman et al., 2007; Staples et al., 2014). (2) Metamorphism in the younger Middle Jurassic to Early Cretaceous metamorphic domain (Finlayson) was pre- to synkinematic, with deformation appearing to slightly outlast metamorphism. Therefore, this metamorphism does not appear to be due to a conductive time lag following the earlier (Early Jurassic) deformational event, but rather is associated with another subsequent deformational event. Therefore, any tectonic model that attempts to address this diachronous pattern of deformation and metamorphism must consider that these events occurred under approximately the same conditions at the same crustal level, but at distinctly different times.

The model must also account for K-Ar and $^{40}Ar/^{39}Ar$ metamorphic cooling ages within the Permian–Triassic metamorphic domain, which indicate this domain was rapidly exhumed to upper-crustal levels in the Early Jurassic (Wanless et al., 1978; Hunt and Roddick, 1991, 1992; Breitsprecher and Mortensen, 2004; Knight et al., 2013; Joyce et al., 2015) prior to the development of transposition fabrics and metamorphism to the northeast in both the Finlayson domain and the structurally deeper Australia Mountain domain. This requires that rocks that previously occupied the middle crust were exhumed by erosion and/or tectonic denudation prior to, or coeval with, the progressive ductile underthrusting and burial of rocks to the northeast, nearer to the foreland. We propose the Early Jurassic to mid-Cretaceous data and observations can be reconciled by the episodic westward ductile underthrusting of new, cool material beneath a critically tapered orogenic wedge propagating toward the foreland.

The Early Jurassic to mid-Cretaceous pattern of structurally downward-younging deformation and metamorphism is strikingly similar to, and in part contemporaneous with, that of the southeastern Canadian Cordillera. In the southeastern Canadian Cordillera, deformation and metamorphism progressed from the Early Jurassic to Eocene (Evenchick et al., 2007, and references therein), with younger events recorded at progressively deeper crustal levels (Parrish, 1995; Simony and Carr, 2011). There, rocks presently in the upper structural levels were buried, heated, and exhumed in the Jurassic (Murphy et al., 1995; Colpron et al., 1996; Crowley et al., 2000; Gibson et al., 2005, 2008), while structurally deeper levels continued to be buried and heated from the Cretaceous to earliest Eocene (Carr, 1991; Parrish, 1995; Gibson et al., 1999, 2005, 2008; Crowley and Parrish, 1999; Crowley et al., 2000; Simony and Carr, 2011). This pattern in the southeastern Canadian Cordillera has been attributed to progressive structural burial and underplating of cooler rocks to the east beneath the hinterland as the orogenic wedge propagated toward the foreland (Parrish, 1995; Brown, 2004; Simony and Carr, 2011). We propose that a similar process was active from Early Jurassic to mid-Cretaceous time in the northern Cordillera.

Originally, critical wedge theory was used to model the mechanics and long-wavelength topography of fold-and-thrust belts and accretionary wedges wherein the brittle deformation can be approximated by Coulomb failure criterion (Davis et al., 1983; Dahlen, 1984). Critical wedge theory suggests that the surface slope of an orogenic wedge is a function of the internal strength of the material in the wedge, and the dip and strength of the basal décollement. Williams et al. (1994) extended the applicability of this theory to thick-skinned orogenic belts by including the effects of temperature-dependent plastic deformation at depths below the brittle-ductile transition. Models that include the effects of ductile flow at depth predict a change in surface slope at the brittle-ductile transition, with a low-angle plateau forming above the interior of the orogen, where both the wedge base and décollement zone are deforming by ductile flow (Williams et al., 1994; Willett et al., 1993). The topographic profiles predicted by the models match the observed topography of large hot orogens (e.g., the Andes and Alps), with the changes in surface slope corresponding to the inferred brittle-ductile transition at depth (Williams et al., 1994; Carminati and Siletto, 1997).

Critical wedge theory proposes that an orogenic wedge will deform internally until it reaches a critical taper, after which if no material is added or removed from the wedge, the wedge then slides stably without internal deformation. If material is accreted to the toe or underplated beneath the advancing wedge, it will again deform internally in order to maintain its critical taper (Davis et al., 1983; Platt, 1986). The addition of material at the base of a wedge during underthrusting will cause the wedge to thicken, and its taper to become supercritical. The predicted result is that even during continued convergence and burial, the upper crust may enter a state of extension, coeval with contraction at depth, in order to regain a stable taper (Platt, 1986). Platt (1986) recognized that such coeval underplating of material beneath the wedge and compensating extension above provide a mechanism for exhuming high-pressure metamorphic rocks to upper-crustal levels in the rear of the wedge. In this model, rocks continuously, or episodically, pass through a cycle of burial, heating, and subsequent exhumation as they are underthrust into the basal shear zone and then displaced upward and ultimately exhumed, through the combined effects of underplating from below and compensating extensional denudation at the surface to maintain a critical taper (cf. Platt, 1986).

Brown (2004) adopted the model of Platt (1986) to explain how mid-crustal levels in the hinterland of the southern Canadian Cordillera could also be exhumed by a similar process, however one that involved ductile underthrusting as opposed to discrete, brittle thrust faulting. A pattern of downward-younging ductile deformation and metamorphism in the hinterland of the southern Canadian Cordillera was interpreted by Parrish (1995) to be consistent with a thrust belt setting, in which rocks were progressively overridden as the wedge migrated toward the foreland. Brown (2004) and Williams and Jiang (2005) refined this model, noting that deformation at the mid- to deep-crustal level is characterized primarily by penetrative flow, not by stacking of discrete thrust sheets and partitioned strain. Brown (2004) suggested that the localized shear zone that underlies the base of the wedge in foreland fold-and-thrust belts becomes a distributed ductile shear zone toward the rear of the wedge (Fig. 7).

Williams and Jiang (2005) suggested that penetratively deformed, high-grade metamorphic rocks characterized by a shallowly dipping transposition fabric (or enveloping surface) with abundant intrafolial folds, and a noncoaxial deformation history represent crustal-scale (kilometers-thick) shear zones. In contrast to localized zones of deformation—detachment surfaces with no coupling—thick shear zones are zones of displacement gradients and therefore allow some kinematic and mechanical coupling with the overlying crust (Tikoff et al., 2002). This is supported by the observation in some orogens where the axial surfaces of upright folds in the upper crust are overturned and become part of the transposition foliation at lower-crustal levels (e.g., Murphy, 1987). This style of penetrative flow within a kilometers-thick section of transposed rock can therefore transport weak midcrustal levels toward the foreland above a strong underlying crust (e.g., basement rocks), while also passively carrying the upper-crustal levels (cf. Williams et al., 2006).

Description of a Spatially and Temporally Transient, Distributed, Kilometers-Thick, Ductile Shear Zone in the Northern Cordillera

Deformational fabrics, and the metamorphic grade at which they formed, are strikingly similar across the various domains in the Yukon-Tanana terrane and the structurally underlying parautochthonous rocks. They are characterized by a shallowly dipping, penetrative, composite transposition foliation (S_T) that is coplanar with the limbs of tight to isoclinal folds (Foster et al., 1985, 1994; Colpron, 1999, 2005; de Keijzer et al., 1999; Gallagher, 1999; Gordey and Ryan, 2005; Berman et al., 2007; Staples et al., 2013, 2014). Relict primary compositional layering, contacts (veins and dikes), a preexisting foliation, and rare rootless isoclinal folds can be traced around these fold closures, indicating the folds are at least F_2 structures. However, it is possible that the preexisting isoclinal folds and the associated axial-planar foliation may have been refolded in a self-similar style during a single, progressive deformation event. There has been very limited detailed structural and kinematic analysis within the hinterland of the northern Cordillera; however, a few studies have observed that the mineral lineation, where present, is parallel to the fold axes of the youngest tight to isoclinal syntransposition folds (F_T; Colpron, 1999; de Keijzer et al., 1999; Dusel-Bacon et al., 2002; Gordey and Ryan, 2005; Berman et al., 2007). Parallelism of the mineral lineation with syntransposition fold axes suggests intense progressive noncoaxial deformation wherein the fold axes have progressively rotated into approximate parallelism with the shear direction (Escher and Watterson, 1974; Williams and Zwart, 1977).

The amphibolite-facies metamorphism, shallowly dipping transposition foliation, and noncoaxial deformation history described here for much of the lowest exposed structural and stratigraphic levels of the Yukon-Tanana terrane and the structurally underlying parautochthonous rocks are consistent with a crustal-scale (kilometers-thick) shear zone as described by Williams and Jiang (2005). Rocks are envisaged as being underthrust and underplated along a discrete brittle thrust fault toward the toe of the wedge, transitioning into a diffuse, kilometers-thick, ductile shear zone at greater depths toward the back of the wedge (Fig. 7). However, in situ U-Pb monazite geochronology on these rocks (Berman et al., 2007; Staples et al., 2013, 2014) demonstrates that the development of this distributed, ductile shear zone was not synchronous throughout the terrane. Rather, the deformation and associated amphibolite facies metamorphism become younger both downward and toward the foreland, similar to that described by Brown (2004) in the southeastern Canadian Cordillera.

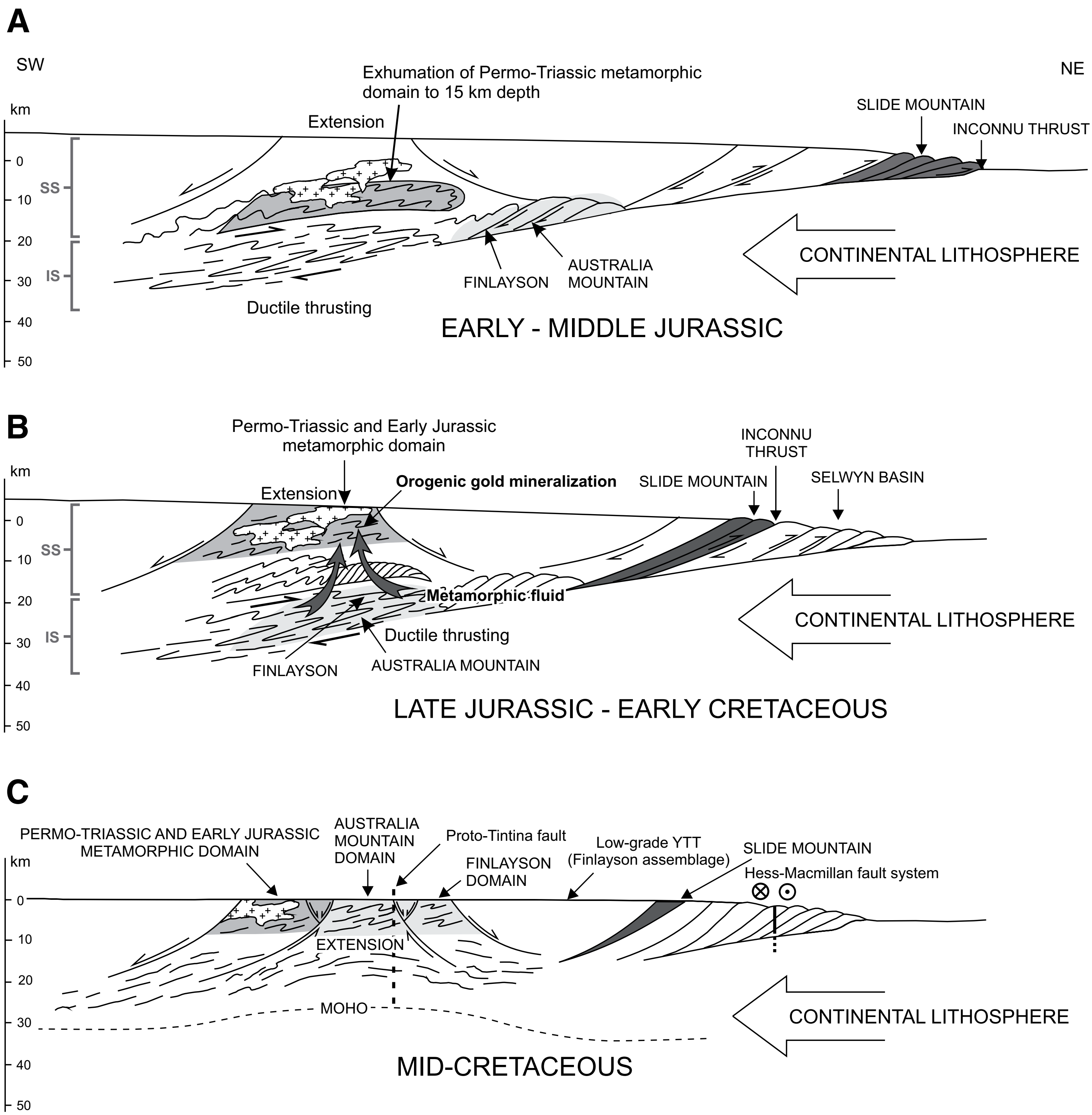

Figure 7. Schematic evolutionary model of the northern Canadian Cordilleran orogenic wedge. (A) Early–Middle Jurassic: The exhumation of rocks previously buried and metamorphosed in the Permian is driven by combined underplating at depth and compensating extensional denudation above in order to maintain a critical taper as the North American crust is underthrust to the west. The Finlayson and Australia Mountain domains may have been underthrust and incorporated into the wedge at this time, but they are still within the cool toe of the wedge. (B) Late Jurassic–Early Cretaceous: Continued underthrusting of the North American crust causes the Finlayson and Australia Mountain domains to be buried and ductilely underthrust to ~25–30 km depth toward the rear of the wedge, causing rocks that had previously occupied this shear zone to be displaced upward due to compensating extension above. The Australia Mountain domain, which was closer to the foreland, or craton, relative to the Finlayson domain in the Permian, was ductilely underthrust and metamorphosed after the Finlayson domain in the Early to mid-Cretaceous, and thus lies structurally beneath the Finlayson domain at this time. Orogen attained a maximum crustal thickness, forming an ~5 km elevated plateau. (C) Mid-Cretaceous: The Finlayson and Australia Mountain domains are exhumed in the mid-Cretaceous along the Australia Creek and Stewart River–North River faults following a change in kinematics. YTT—Yukon-Tanana terrane.

The development of transposition fabrics at amphibolite facies occurred diachronously within the Yukon-Tanana terrane in the Permian–Triassic, Early Jurassic, Middle Jurassic to Early Cretaceous, and Early to mid-Cretaceous (Berman et al., 2007; Beranek and Mortensen, 2011; Staples et al., 2013, 2014). However, each event occurred at approximately the same crustal level (7.5–9 kbar, or 25–30 km depth; Berman et al., 2007; Staples et al., 2013, 2014) and resulted in a widespread tectonic pile of schist and gneiss with similar appearance. This requires that rocks that previously occupied the distributed ductile shear zone in the middle crust were subsequently exhumed by erosion and/or tectonic denudation prior to, or coeval with, the progressive ductile underthrusting and burial of subsequent rocks to midcrustal levels.

The repeated cycling of rocks down into the distributed shear zone and then upward into the overlying crust implies that rocks that occupy the upper crust at any time may contain older, relict structures that are identical to the deformational and metamorphic fabrics forming at the same time in the midcrustal, distributed shear zone. In addition to these shallowly dipping, high-grade, penetrative fabrics that develop within the ductile shear zone at depth, upright, brittle structures overprint the earlier ductile fabrics at lower metamorphic grade as they are progressively exhumed to upper-crustal levels. We apply the term "infrastructure" in a similar sense to that suggested by De Sitter and Zwart (1960) and Culshaw et al. (2006) when describing mid- to lower-crustal levels in an orogen characterized by high-grade, shallowly dipping, ductilely deformed and transposed rocks. Conversely, the overlying "suprastructure" would be characterized by upright, brittle structures and low metamorphic grade. In the northern Cordillera, this rheological contrast between upper- and lower-crustal levels is time specific. We make this distinction because, as explained already, rocks formerly situated in the lower crust, the infrastructure, were progressively exhumed in the Jurassic and incorporated into the suprastructure above the Middle Jurassic to Early Cretaceous infrastructure (Fig. 7). However, not all rocks within the suprastructure had occupied the infrastructure. For example, there is a panel of weakly deformed and essentially unmetamorphosed rocks with Carboniferous cooling ages in this part of the orogen (Figs. 3 and 4), indicating that this panel has occupied a high crustal level since the Carboniferous.

Early Jurassic Wedge

Abundant evidence of Early Jurassic contraction, imbrication, and metamorphism within the Yukon-Tanana and Slide Mountain terranes (Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2002; Berman et al., 2007; Murphy et al., 2006) suggests that by this time, these terranes had been thrust onto the continental margin, forming an orogenic wedge above the westward-migrating and underthrusting North American continent (Figs. 7A and 8A; Nelson et al., 2006). Early Jurassic exhumation of the Permian–Triassic metamorphic domain of the Yukon-Tanana terrane, as revealed from widespread Early Jurassic K-Ar and $^{40}Ar/^{39}Ar$ cooling ages, is interpreted as the response to underplating of new material and thickening the wedge beyond its critical taper as the wedge propagated eastward.

Early Jurassic uplift and exhumation in the upper levels of the wedge are contemporaneous with, or immediately follow, contraction and burial at depth. Uplift and exhumation is recorded by K-Ar and $^{40}Ar/^{39}Ar$ cooling ages in the Permian-Triassic domain, which overlap with U-Pb metamorphic monazite ages that are linked to an ~7.6 kbar (≈ 25 km depth) metamorphic event (Berman et al., 2007). Additionally, clast types and provenance studies of the Early to Middle Jurassic Laberge Group in the Whitehorse trough (Fig. 2; Colpron et al., 2015) show a temporal transition from volcanic clasts to sedimentary clasts to granitic clasts, which record the erosion of the Lewes River arc (Stikine terrane), progressing to shelf uplift, and then uplift and erosion of the arc's plutonic roots, respectively, during the Early Jurassic (Dickie and Hein, 1995; Hart et al., 1995; Hart, 1997). Dusel-Bacon et al. (2002) also document syncollisional exhumation in east-central Alaska, where they interpreted Early Jurassic (ca. 188–186 Ma) $^{40}Ar/^{39}Ar$ cooling ages in amphibolite-facies rocks of the Yukon-Tanana terrane to record cooling during northwest-directed contraction (thrust faulting) that emplaced these rocks above greenschist-facies rocks of the Yukon-Tanana terrane. At approximately this same time, Knight et al. (2013) documented extension within Yukon-Tanana terrane in west-central Yukon. There, amphibolite-facies rocks that were metamorphosed in the Permian and Early Jurassic (Staples, 2014; Knight et al., 2013) and contain Early Jurassic $^{40}Ar/^{39}Ar$ cooling ages (Knight et al., 2013), are juxtaposed across the Willow Lake normal fault against essentially unmetamorphosed and predominantly undeformed Devonian and Mississippian rocks of the Yukon-Tanana terrane that preserve Mississippian $^{40}Ar/^{39}Ar$ cooling ages (Figs. 3 and 4).

The underthrusting of cooler rocks that gradually made their way toward the back of the wedge in the Early Jurassic would have provided a new source of hydrous material from which fluids may have been derived via dehydration reactions upon heating of these newly buried rocks. Migration of this fluid upward into overlying rocks, which were previously metamorphosed and dehydrated in the Permian, but were subsequently displaced upward and exhumed in the Early Jurassic, may have provided the catalyst for renewed metamorphic reactions and Early Jurassic retrograde monazite growth (ca. 187 Ma; Berman et al., 2007) in that overlying, partially exhumed panel (Permian–Triassic domain in Fig. 7A). The introduction of reaction catalyzing fluids contemporaneous with exhumation would explain the overlap of Early Jurassic U-Pb metamorphic monazite and regional $^{40}Ar/^{39}Ar$ cooling ages (Berman et al., 2007). Additionally, strain may have been localized within zones of enhanced fluid flow, which may explain the absence of a ubiquitous penetrative ductile fabric, but rather the more discrete, localized deformation associated with metamorphism in the Early Jurassic. Deformation may also have been localized where fluids evolved from the Early Jurassic intrusions.

Middle Jurassic to Mid-Cretaceous Wedge

Widespread Early Jurassic cooling ages across the northern Yukon-Tanana terrane reveal that rocks metamorphosed in the Permian–Triassic remained at a high structural level from the Early Jurassic onward. By contrast, the highly transposed nature, *P-T* data, and U-Pb monazite geochronology indicate that rocks in the Finlayson and Australia Mountain domains were being buried, heated, and incorporated into a distributed, ductile shear zone at 25–30 km depth in the Middle Jurassic to mid-Cretaceous (Fig. 7B; Staples et al., 2013, 2014). The apparent absence of Permian–Triassic and Early Jurassic metamorphism in these younger domains to the northeast, as well as *P-T-t* data that reveal a pattern of structurally downward-younging deformation and metamorphism (169–142 Ma at ~25 km depth for Finlayson, and 146–118 Ma at ~30 km depth for Australia Mountain; Staples et al., 2013, 2014), is interpreted to correspond with the progressive underthrusting of new material as the orogenic wedge propagated toward the foreland (Fig. 6B).

The current geometry of the Middle Jurassic to mid-Cretaceous metamorphic domains does not, however, show the predicted foreland-younging pattern. Instead, the ca. 146–118 Ma Australia Mountain domain lies southwest (outboard) of the older (ca. 169–142 Ma) Finlayson domain (Figs. 4 and 5). As outlined already, the Australia Mountain domain is interpreted to represent parautochthonous rocks of the North American margin that were exhumed from beneath the Yukon-Tanana terrane in the mid-Cretaceous and thus presumably originated east of the Finlayson do-

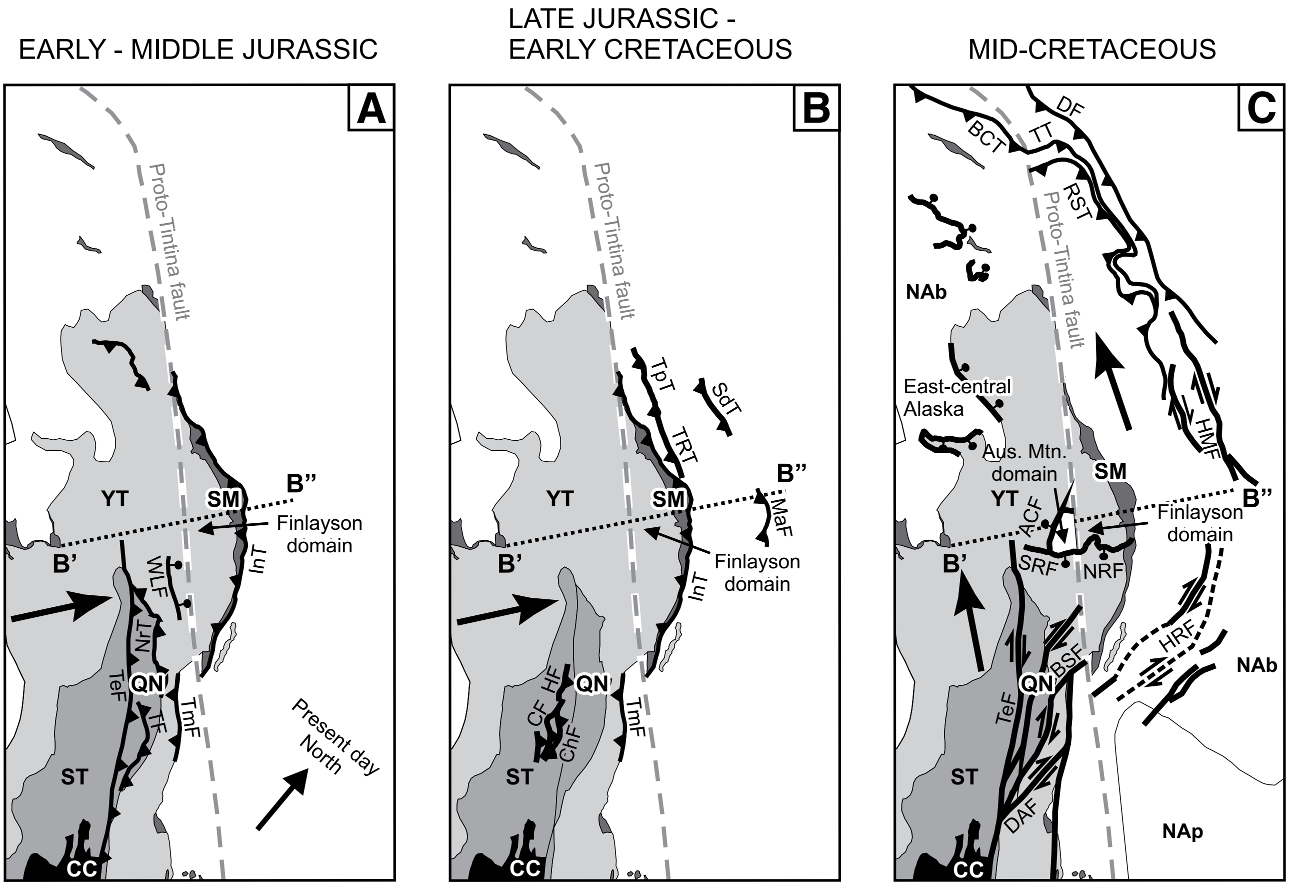

Figure 8. Generalized geological maps illustrating the orientation and kinematics of active structures at the time of each corresponding wedge section in Figure 7. Note, the geological maps are essentially static, in that they do not account for the amount of shortening during each time frame, and they are thus not a true plan view of what is shown in cross sections in Figure 7. Large black arrows illustrate the direction of crustal transport. The southwest-northeast–trending dotted line from B′ to B″ is the approximate location of the schematic wedges in Figure 7. (A) Early–Middle Jurassic: characterized by northeast- and southwest-vergent thrust faults, reflecting a dynamic of orogen-normal compression and vertical extension (crustal thickening). (B) Late Jurassic–Early Cretaceous: Northeast- and southwest-vergent thrusts related to continued orogen-normal compression and vertical extension. (C) Mid-Cretaceous: This time was characterized by a change in the orogen's dynamics from orogen-normal shortening and thickening to lateral (orogen-parallel) extension as interpreted for the Stewart River and North River faults and comparable faults in east-central Alaska (Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2002). Fault abbreviations: ACF—Australia Creek fault; BCT—Beaver Creek thrust; BSF—Big Salmon fault; CF—Coghlan fault; ChF—Chain fault; DAF—D'Abbadie fault; DF—Dawson fault; HF—Hoochekoo fault; HMF—Hess-Macmillan fault system; HRF—Hyland River fault system; InT—Inconnu thrust; MaF—March fault; NRF—North River fault; NrT—Needlerock thrust; RST—Robert Service thrust; SdT—Sheldon thrust; SRF—Stewart River fault; TaF—Tadru fault; TeF—Teslin fault; TF—Towhata fault; TmF—Tummel fault; TT—Tombstone thrust; TpT—Twopete thrust; TRT—Tay River thrust; WLF—Willow Lake fault. City abbreviations: D—Dawson; Fb—Fairbanks; RR—Ross River; Wh—Whitehorse; WL—Watson Lake. Terrane abbreviations: CC—Cache Creek; QN—Quesnellia; ST—Stikine; YT—Yukon-Tanana; Nab—North America basinal strata; Nap—North America platform strata.

main (Fig. 6A). The present exposure of the Australia Mountain domain west of the Slide Mountain terrane and the Finlayson domain is attributed to underthrusting of the Australia Mountain domain down to the west beneath the obducting Yukon-Tanana (Finlayson domain) and Slide Mountain terranes in the Early to mid-Cretaceous, and possibly earlier (Figs. 6B, 7A, and 7B), following burial and metamorphism of the Finlayson domain in the Middle Jurassic to Early Cretaceous. Elongate lenses of metamorphosed ultramafic rock consisting of tremolite and talc (tens of meters thick) occur within the Australia Mountain domain (Fig. 3) and are concordant with the regional transposition foliation. These altered ultramafic lenses may represent slivers of Slide Mountain terrane that were incorporated into, and interfoliated with, parautochthonous rocks of the Australia Mountain domain within a diffuse (kilometers-thick) shear zone during underplating of the Australia Mountain domain (Fig. 6B). Subsequent extensional exhumation of the Australia Mountain domain from beneath the overlying Yukon-Tanana terrane in the mid-Cretaceous placed the Australia Mountain domain in its present location adjacent to, and west of, the Finlayson domain of the Yukon-Tanana terrane (Fig. 7C).

The underplating of material in the Finlayson and Australia Mountain domains beneath an orogenic wedge as it propagated toward the foreland from Middle Jurassic to mid-Cretaceous time is thought to have been driven primarily by continued westward migration and underthrusting of the North American craton during the opening of the Atlantic Ocean basin, and continued convergence of an ocean basin outboard to the west. Accretion of the Insular terranes outboard of the Yukon-Tanana terrane in the Early to Middle Jurassic may have provided an additional force driving the wedge toward the foreland during the Middle Jurassic to mid-Cretaceous. However, as was discussed earlier in the manuscript, the dynamics outboard (to the west) of this portion of the Yukon-Tanana terrane at this time are not well constrained, with often conflicting interpretations.

Possible Origin of Late Jurassic Gold-Bearing Metamorphic Fluids

Underplating, heating, and devolatilization of cool, hydrous material in the Finlayson domain in the Middle Jurassic to Early Cretaceous may have provided a source of fluids for Late Jurassic "orogenic" gold-bearing veins (Bailey, 2013; Allan et al., 2013) within the structurally overlying, colder, and previously dehydrated rocks of the Permian–Triassic metamorphic domain (Figs. 3 and 7B). Gold-bearing quartz veins at the Golden Saddle deposit were emplaced along brittle structures (Bailey, 2013) within rocks previously metamorphosed in the Permian–Triassic (and Early Jurassic?; Berman et al., 2007). The timing of mineralization is constrained by ^{187}Re/^{187}Os model ages of 163–155 Ma from molybdenite interpreted to be paragenetically related to the gold (Bailey, 2013). These ages are contemporaneous with amphibolite-facies metamorphism, devolatilization, and ductile deformation (ca. 169–142 Ma) at deeper crustal levels in the Finlayson domain (Staples et al., 2014), and thus they provide a possible metamorphic fluid source for the gold-bearing veins. However, data from this study do not provide insight as to the source of gold. A similar general model for postmetamorphic gold vein development was published by Stüwe et al. (1993) and Stüwe (1998), except their model attributed the diachronous metamorphism at depth to a single tectonic thickening event, rather than the separate burial and metamorphic events constrained in our study. Middle to Late Jurassic ^{40}Ar/^{39}Ar cooling ages (174–144 Ma; Joyce et al., 2015) from hornblende and micas near areas of gold mineralization are anomalous relative to more widespread Early Jurassic cooling ages in the surrounding regions (195–180 Ma; Joyce et al., 2015) and may indicate resetting of the Ar system during localized circulation of these metamorphic fluids.

MID-CRETACEOUS—A CHANGING GEODYNAMIC

Thin-skinned, northeast-vergent, regional-scale folds and shallow-dipping thrust faults in the Selwyn Basin immediately to the northeast of Yukon-Tanana terrane and the Finlayson domain (Fig. 8B) are bracketed between Early and mid-Cretaceous (Gordey, 2013), coeval with Late Jurassic to mid-Cretaceous thick-skinned deformation in the Finlayson and Australia Mountain domains. The northeastward, foreland-directed, migration of ductile deformation and amphibolite-facies metamorphism into the Finlayson and Australia Mountain domains and northeast-vergent folding and thrust-faulting within the foreland record orogen-normal (northeast-directed) contraction and thickening across the northern Cordilleran orogen until the mid-Cretaceous. Peak metamorphic pressures of 7.5 and 9 kbar from rocks presently exposed at the surface in the Finlayson and Australia Mountain domains (Staples et al., 2013, 2014), respectively, correspond to ~25–30 km depth. Considering the Moho is currently located at ~35 km depth in the northern Cordillera (Cook and Erdmer, 2005), this suggests the crust was as much as 60–65 km thick prior to mid-Cretaceous exhumation. Gibson et al. (2008) determined a similar crustal thickness in the southeastern Canadian Cordillera and, on the basis of local Airy isostasy, suggested this would have produced a high-standing plateau at least 5 km above sea level.

The Albian (113–100 Ma) Indian River formation (Lowey and Hills, 1988), located ~35 km west of the Australia Mountain domain in the hanging wall of the Australia Creek fault (Fig. 3), was deposited roughly coeval with extensional exhumation of the Australia Mountain domain. In addition to both the synchronicity between deposition of the Indian River formation and exhumation of the Australia Mountain domain, as well as its location in the hanging wall of the Australia Creek fault, the Indian River formation contains metamorphic detritus (quartz with undulatory extinction, and lesser amounts of muscovite, feldspar, and foliated lithic fragments; Lowey and Hills, 1988), which together suggests it represents a synextensional detachment basin to the Australia Creek fault. The presence of the dinoflagellate *Muderongia asymmetrica* within the Indian River formation was interpreted by Lowey (1984) to indicate deposition in a marine-influenced environment, requiring that this portion of the hinterland of the northern Cordillera had been reduced to sea level by 113–100 Ma. Reduction of the metamorphic hinterland to sea level by 113–100 Ma by extension along the Australia Creek fault indicates that the orogenic wedge had collapsed by this time, and that extensional denudation along the Australia Creek and Stewart River–North River faults was extremely rapid. This is corroborated by both 116–104 Ma K-Ar and ^{40}Ar/^{39}Ar hornblende and mica cooling ages (Hunt and Roddick, 1992; Staples, 2014), and a younger generation (ca. 112 Ma) of texturally and chemically distinct (Y-rich) monazite grains at Australia Mountain, interpreted by Staples et al. (2013) to record the timing of decompression from ~30 km depth following peak metamorphism at ca. 118 Ma at (Staples et al., 2013).

The northwest-southeast–trending Australia Creek fault is cut by the southwest-northeast–trending Stewart River–North River fault (Figs. 3 and 4); therefore, exhumation of the Australia Mountain domain likely began along the Australia Creek fault. Tilting of the footwall during exhumation along the Australia Creek fault may explain the exposure of the deepest crustal level in the Australia Mountain domain closest to the fault, and a slightly higher crustal level in the Finlayson domain to the northeast further from the fault. Alternatively, an unnamed, roughly northeast-dipping normal fault, hidden within the Tintina trench (Fig. 5), may have accommodated enough displacement to account for the 5 km of structural relief between these two domains. Furthermore, if this hidden fault is shallowly dipping, the Finlayson domain would restore directly above the Australia Mountain domain. A normal fault of this orientation would explain how the youngest metamorphic domain is exposed west (outboard) of the Finlayson district, contrary to the overall pattern of northeastward younging of deformation and metamorphism toward the foreland.

Subsequent mid-Cretaceous extension along the Stewart River and North River faults is interpreted to document northwest-southeast orogen-parallel extension (Fig. 8C). Similar southeast-directed extension is documented less than 200 km to the west in east-central Alaska, where parautochthonous North American continental margin rocks (Lake George assemblage in Fig. 2) were exhumed from beneath the Yukon-Tanana terrane along mylonitic extensional faults in the mid-Cretaceous (Pavlis et al., 1993; Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2002). The timing of this extensional exhumation in east-central Alaska, as constrained by ca. 135–110 Ma ^{40}Ar/^{39}Ar cooling ages (Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2002), was approximately coeval with extension in west-central Yukon.

Lateral (Orogen-Parallel) Extrusion

Roughly coeval with the onset of orogen-parallel extension, the Cordilleran orogen records a shift to transpressional tectonics, initially marked by the development of sinistral strike-slip faults in western British Columbia beginning at ca. 123 Ma (Nelson et al., 2011, 2013). By ca. 115–95 Ma, a system of dextral strike-slip faults had developed in northern British Columbia and south-central Yukon (Gabrielse et al., 2006), coeval with the most active episode of sinistral strike-slip faulting in western British Columbia and Alaska. The dextral strike-slip system in northern British Columbia and south-central Yukon feeds into the northwest-directed Tombstone and Beaver Creek thrust faults in north-central Yukon and east-central Alaska, respectively (Figs. 8C; Gabrielse et al., 2006), which are interpreted as defining the leading edge of a crustal block escaping laterally to the northwest in the mid-Cretaceous (Fig. 9; Nelson et al., 2013; Angen et al., 2014). The zones of orogen-parallel extension in the Australia Mountain, Finlayson, and east-central Alaska domains lie within this crustal block and were extended simultaneously with movement along these bounding strike-slip faults.

The shift in kinematics within this portion of the orogen, with orogen-normal compression dominating through the Jurassic and Early Cretaceous (Figs. 8A and 8B) transitioning to orogen-parallel strike-slip faulting and extension in the mid-Cretaceous (Fig. 8C), coincides with a change in the trajectory of the North American plate from west-northwest to west-southwest at ca. 110 Ma (Elston et al., 2002; Nelson et al., 2013). This resulted in a change from sinistral-oblique to near-orthogonal convergence between the North American and Farallon plates (Engebretson et al., 1985), and presumably an ensuing increase in the orogen-normal component of horizontal stress. The development of orogen-parallel strike-slip faults and extension during orthogonal plate convergence is supported by the work of Angen et al. (2014), who observed that mid-Cretaceous orogen-parallel sinistral strike-slip faults in western British Columbia developed as part of a conjugate set in a regime of east-northeast–west-southwest (orogen-normal) shortening. Orthogonal convergence in the mid-Cretaceous is further attested to by an abundance of orogen-normal shortening along

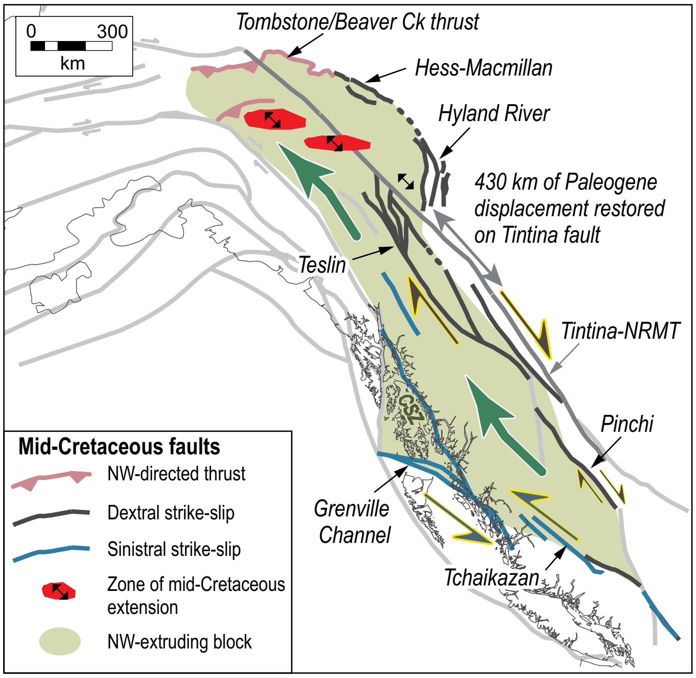

Figure 9. Mid-Cretaceous extensional zones (in red) in east-central Alaska and Yukon (Finlayson and Australia Mountain domains) are located near the leading edge of a northwestward-extruding block (in green). The block is bounded to the southwest by series of sinistral strike-slip faults (Grenville Channel and Tchaikazan), whereas roughly coeval dextral strike-slip faults mark the northeastern edge (Hyland River, Hess-Macmillan) and feed into the NW-directed Tombstone and Beaver Creek thrusts, which define the leading edge of this extruding block. Approximately 430 km of displacement, and offset of Yukon-Tanana terrane, has been restored along the Paleogene Tintina fault (in grey) (modified from Nelson et al., 2013). NMRT—Northern Rocky Mountain Trench.

the coast in western British Columbia and southeast Alaska (Crawford et al., 1987; McClelland et al., 1992; Rubin and Saleeby, 1992; Journeay and Friedman, 1993) as well as across the orogen (Evenchick et al., 2007) in the mid-Cretaceous.

Thickening of the lithosphere in the foreland fold-and-thrust belt to the northeast, possibly coupled with the impingement of this foreland-propagating orogenic wedge against a crustal ramp inherited from late Proterozoic or Paleozoic rifting, may have built up a sufficiently strong buttress, such that it became easier to accommodate continued orogen-normal convergence by lateral (orogen-parallel) escape, as opposed to orogen-normal shortening. This lateral displacement may have been aided by lateral spreading (orogen-parallel extension) driven by gravitational body forces along an orogen-parallel elevation gradient (e.g., Dewey, 1988; England and Houseman, 1989). Numerical simulations suggest that the lateral gravitational body forces developing in weak thick crust, such as would be expected in the Australia Mountain domain in the Early Cretaceous, given peak metamorphic conditions of 650–680 °C and 9 kbar pressure (Staples et al., 2013), would contribute to the lateral displacement of rock normal to the direction of plate convergence (Liu and Yang, 2003; Robl and Stüwe, 2005). We envision that orogen-parallel extension along the Stewart River–North River fault and similar extension in east-central Alaska (Pavlis et al., 1993; Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2002) resulted from a deviatoric tension set up along an orogen-parallel elevation gradient and contributed to the lateral displacement of rocks normal to the direction of shortening during plate convergence. We follow Robl and Stüwe (2005) and refer to the accommodation of convergence through this combined process of forced lateral motion of crustal blocks away from the zone of convergence under overall compression ("tectonic escape") and lateral displacement driven by deviatoric tension along a gravitational potential energy gradient ("gravitational collapse") as "lateral extrusion." This model is similar to the "gravitational spreading" model ("model C") of Pavlis et al. (1993), which was one of three end-member models proposed to explain the same mid-Cretaceous extension within the Yukon-Tanana terrane in east-central Alaska.

A similar shift from crustal thickening to orogen-parallel extension in the orogen's interior, contemporaneous with orthogonal convergence, has also been documented in the Anatolian region of Turkey (Dewey et al., 1986), and the Tauern Window in the Alps, where orogen-parallel extension has exhumed high-grade metamorphic core complexes (Selverstone, 1988; Ratschbacher et al., 1991). Furthermore, three-dimensional thermo-mechanical modeling by Seyferth and Henk (2004) predicted that orogen-parallel extension is intimately related to continental collision and occurs contemporaneously with orogen-normal convergence. We observed similar structures as those predicted by the modeling results of Seyferth and Henk (2004). Within the northern Cordilleran orogen, there is a zone of orogen-parallel extension within the core (metamorphic hinterland), which is bounded by a zone of strike-slip faults that separate it from orogen-normal shortening in the peripheral fold-and-thrust-belts (Fig. 9).

A gravitational body force has also been proposed to explain east-west, orogen-parallel extension in Tibet that was likewise synchronous with, and proposed as a contributing force for, the lateral, orogen-parallel extrusion of eastern Tibet and China simultaneous with shortening driven by orthogonal plate convergence (Dewey et al., 1989; England and Houseman, 1989; Robl and Stüwe, 2005).

Many orogens that exhibit a similar coupling between orogen-parallel extension and lateral extrusion occur in regions of orthogonal plate convergence that are laterally unconstrained, thus allowing material to flow out. In fact, in some areas with an unconstrained lateral boundary, slab rollback is considered to be a tensional force driving extension. Determining whether a similar unconstrained lateral boundary existed at the northwestern extent of the Cordillera is complicated by a combination of post–mid-Cretaceous strike-slip faulting (Box, 1985; Miller et al., 2002), the Early Cretaceous opening of the Canada Basin in the Arctic Ocean, and related rotation of terranes in northern Alaska, making paleotectonic reconstruction very difficult. In orogens with a rigid lateral boundary, extension is balanced by thrust faulting that partially surrounds the extensional domains at a high angle, and is thus not directly related to the direction of plate convergence (Dewey, 1988; Seyferth and Henk, 2004). Peripheral northwest-directed thrusting along the Tombstone and Beaver Creek thrust faults, broadly constrained to the Jurassic–Cretaceous (Fig. 9; Murphy, 1997), may have thus served to balance the northwest-southeast–directed extension in west-central Yukon and east-central Alaska.

CONCLUSIONS

Transposition fabrics and the associated amphibolite-facies metamorphism that is nearly ubiquitous throughout the northern Yukon-Tanana terrane and the underlying parautochthonous North American rocks did not develop during a single tectono-metamorphic event. Rather, ductile deformation and amphibolite-facies metamorphism developed diachronously, with events recorded in the latest Middle Permian–Middle Triassic, Early Jurassic, Middle Jurassic to Early Cretaceous, and Early to mid-Cetaceous. Rocks deformed and metamorphosed in the Permian–Triassic were exhumed in the Early Jurassic, while rocks to the northeast (toward the foreland) within Yukon were progressively buried and heated from Middle Jurassic to mid-Cretaceous time, with deformation and metamorphism becoming younger at progressively deeper crustal levels. These data reveal that deformation and metamorphism migrated toward the foreland and structurally downward in the Middle Jurassic to mid-Cretaceous.

These data and observations are reconciled by the critically tapered wedge theory, in which cooler rocks in front of the wedge were episodically underthrust, buried, and metamorphosed from the Jurassic to mid-Cretaceous beneath an orogenic wedge propagating toward the foreland at critical taper. Rocks that were previously metamorphosed and ductilely deformed in the Permian–Triassic were displaced upward and exhumed through the combined effects of renewed underplating at depth and compensating extensional denudation above in order to maintain a critical taper. Following on the work of Brown (2004) to explain similar patterns in the hinterland of the orogen in the southeastern Canadian Cordillera, we interpret that the localized shear zone that underlies the base of the wedge in the foreland thrust-and-fold belt became a distributed (kilometers-thick) ductile shear zone (transposition zone) toward the rear of the wedge (hinterland). This zone was a transient feature beneath the propagating wedge as new material was underthrust and incorporated into the distributed shear zone in the Jurassic to mid-Cretaceous, causing rocks that had previously occupied this zone to be displaced upward into the overlying wedge and ultimately exhumed.

Rocks that occupied the midcrustal shear zone in the Middle Jurassic to mid-Cretaceous (Finlayson and Australia Mountain domains) were first exhumed in the mid-Cretaceous along the Australia Creek fault from beneath a supracrustal "lid" that had previously been metamorphosed and ductilely deformed and transposed at amphibolite facies in the Permian–Triassic and Early Jurassic. Extensional exhumation of the metamorphic hinterland along the Australia Creek fault in the mid-Cretaceous marked the collapse and end of the orogen-perpendicular wedge dynamics in operation since the Early Jurassic. Continued mid-Cretaceous extension along the Stewart River and North River faults, and comparable faults in east-central Alaska (Hansen and Dusel-Bacon, 1998; Dusel-Bacon et al., 2002), records a shift in the orogen's dynamics with extension now directed laterally, parallel to the length of the orogen. The development of an internal zone of orogen-parallel extension, bounded by strike-slip faults, during a period of increasingly orthogonal plate convergence, suggests that continued orogen-normal convergence in the mid-Cretaceous was being accommodated by lateral (orogen-parallel) extrusion, as opposed to continued orogen-normal shortening. Metamorphic cooling ages, as well as evidence of marine deposition within a synextensional detachment basin (Indian River formation) to the Australia Creek fault, require that extensional denudation along the Australia Creek, Stewart River, and North River faults was extremely rapid, and that the orogenic wedge had collapsed and was reduced to sea level by ca. 110–100 Ma.

We would suggest that the diachroneity of deformation and metamorphism discussed for the northern Canadian Cordillera is probably not an exception, but rather the norm for accretionary orogenic systems that are long lived and multi-episodic.

ACKNOWLEDGMENTS

This work was funded by Natural Sciences and Engineering Research Council of Canada (NSERC) grants to Colpron and Gibson, and a NSERC scholarship to Staples. Additional support was provided through the Geological Survey of Canada's (GSC) Geomapping for Energy and Minerals Program (ESS contribution 20140467). The manuscript benefited from discussions with Rob Berman, Joel Angen, Bill McClelland, Don Murphy, and Cees van Staal. We thank Jane Gilotti and Sarah Roeske for thorough and insightful reviews that greatly improved the manuscript. We thank Kurt Stüwe for editorial handling of the manuscript. This is Yukon Geological Survey contribution number 026.

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MANUSCRIPT RECEIVED 17 JUNE 2015
REVISED MANUSCRIPT RECEIVED 18 DECEMBER 2015
MANUSCRIPT ACCEPTED 11 JANUARY 2016

Printed in the USA