The timing and provenance record of the Late Permian Klondike orogeny in northwestern Canada and arc-continent collision along western North America

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[1] The northern Canadian Cordillera exhibits coeval accreted arc, subduction zone, ocean basin, and continental margin assemblages that make the region an exceptional place to understand tectonic processes involved in arc-continent collision. In this study, we use U-Pb zircon and monazite geochronology to define the timing and provenance record of Late Permian collisional orogeny related to the accretion of the Yukon-Tanana terrane onto the ancestral North American continental margin of northwestern Canada. New U-Pb crystallization ages of Permian intrusive rocks in the Klondike District of western Yukon bracket the timing of collision-related ductile deformation and greenschist- to amphibolite-facies metamorphism on the Yukon-Tanana terrane between 260 and 252.5 Ma. This tectonothermal event is herein named the Klondike orogeny. Detrital zircon U-Pb geochronology of Triassic strata provides the sedimentary record of arc-continent collision and crustal reworking along the Cordilleran margin. Arc-derived detrital zircons in Early to Middle Triassic (251–235 Ma) strata overlying the ancestral North American continental margin in Yukon suggest that a foreland-style basin developed adjacent to the Klondike orogen. Regionally extensive Late Triassic (235–200 Ma) strata containing primarily North American detrital zircons form an overlap assemblage that covered the accreted terranes and western North America. The timing of the Klondike orogeny is roughly synchronous with other contractional events along the ~5000 km strike length of the Cordillera, including the Late Permian-Early Triassic Sonoman orogeny in Nevada. Global plate reorganization linked to assembly of Pangaea may have been the tectonic engine for late Paleozoic-early Mesozoic development of the North American Cordillera.

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1. Introduction

[2] The geological and geophysical records of magmatism, metamorphism, and sedimentation in mountain belts, or orogens, are critical to constrain the timing of tectonic processes that operate along convergent plate margins. In particular, understanding the ages of discrete tectonothermal events, referred to as orogenies, is essential for determining the scales and drivers of tectonism. For example, spatially extensive and synchronous tectonothermal activity along the length of an orogen generally results from major plate reorganization or supercontinent assembly, whereas localized or diachronous orogeny is more consistent with the effects of ridge subduction, flat-slab subduction, or accretion of buoyant lithosphere [*Cawood and Buchan*, 2007; *Cawood et al.*, 2009]. The classification of orogen type as collisional or accretionary is therefore valuable to define the timing and pattern of tectonothermal events. Collisional orogens classically form at the termination of a Wilson Cycle when the closure of an ocean basin culminates in continent-continent collision, such as that documented by the Eurasian, African, and Indian plates involved in the Alpine-Himalayan mountain chain [*Şengör*, 1987]. Collisional orogens fundamentally represent sites where pre-existing crustal material is reworked. In contrast, accretionary orogens lie along plate margins that have experienced long-lived subduction and accretion, such as the modern Cordilleran orogen of western North America [*Cawood et al.*, 2009]. Accretionary orogens are constructed along the periphery of continents and comprise some of the most important locations of net crustal growth on Earth [*Condie*, 2007]. The timing of collisional and accretionary orogen development may be ultimately linked by global plate reorganization; *Cawood and Buchan* [2007] concluded that collisional orogenesis related to the assembly of supercontinent Pangaea was synchronous with the

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initiation of subduction and orogenesis within late Paleozoic-early Mesozoic accretionary orogens along the Pacific margin of Gondwana.

[3] The North American Cordillera is an active accretionary orogen with a strike length of ~5000 km, stretching from the Arctic Ocean southward to Mexico (Figure 1). This orogen continues to be relevant for addressing fundamental topics in global tectonics because the concept of terrane accretion was initially conceived in the North American Cordillera to explain the faulted juxtaposition of arc, oceanic, and continental fragments along the western margin of Laurentia (ancestral North America) [*Coney et al.*, 1980]. Terrane accretion is the process by which a downgoing plate introduces buoyant arc or continental crust into a subduction zone, resulting in collisional orogenesis [*Cloos*, 1993]. Under this definition, subduction of the Eurasian margin beneath the Luzon arc in Taiwan is a modern example of arc-continent collisional orogenesis [e.g., *Huang et al.*, 2006].

[4] There is general agreement among Cordilleran workers that the belts of arc (Yukon-Tanana, Quesnellia, northern Sierra, eastern Klamath) and oceanic (Slide Mountain) terranes that crop out immediately west of the ancestral North American continental margin (Figure 1) were generated adjacent to the western edge of Laurentia as a series of rifted continental fragments, superposed arcs, and marginal ocean basins in mid- to late Paleozoic time [*Rubin et al.*, 1990; *Nelson et al.*, 2006]. These so-called pericratonic (continent margin-fringing) terranes formed in a manner analogous to the modern Japanese arc-Sea of Japan backarc system alongside the eastern Eurasian margin [*Colpron et al.*, 2007]. The paucity of geochronological constraints on pericratonic terrane evolution, most notably the timing of late Paleozoic to Mesozoic arc-continent collision and terrane accretion along the length of western North America, has led to difficulties in deciphering the tectonic setting and global significance of convergent margin processes in the Cordilleran orogen. From northern Canada to southern United States, the tectonic collapse of the Cordilleran marginal basins is only broadly documented by the thrust imbrication of oceanic rocks and regional unconformities [e.g., *Gabrielse et al.*, 1983]. The inferred type area for such collisional tectonics in the North America Cordillera is the Great Basin of the western United States, where marginal ocean rocks comprising the Golconda allochthon (Figure 1) were folded and thrust eastward onto the ancestral North American continental margin during the Late Permian-Early Triassic Sonoman orogeny [*Silberling and Roberts*, 1962; *Miller et al.*, 1992; *Dickinson*, 2004]. An unsolved problem in the evolution of the North American Cordillera is the timing and driving force responsible for emplacement of the Golconda allochthon, and as a consequence, the overall relevance of Late Permian-Early Triassic plate convergence to orogen development. One of the more popular tectonic scenarios considers the Sonoman orogeny as the product of terrane accretion [e.g., *Speed*, 1979], whereby the Golconda allochthon was thrust onto the ancestral North American continental margin during east-propagating arc-continent collision. Volcanic sequences in arc terranes west of the Golconda allochthon that were deformed and uplifted during the Late Permian-Early Triassic support this collisional model [*Wyld*, 1991]. Significant challenges for understanding the actual age of this late Paleozoic-early Mesozoic tectonism include a profound absence of geological elements typical of arc-continent collision, such as blueschist and eclogite paired with arc successions and collision-related foreland basin sequences along the ancestral North American continental margin [*Dickinson*, 2006].

[5] Key insights into the timing and significance of pericratonic terrane accretion are potentially recorded by felsic magmatic and high-pressure convergent margin rocks associated with the Middle to Late Permian Klondike arc, which is the youngest arc assemblage of the Yukon-Tanana terrane in northwestern Canada (Figure 2) [*Colpron et al.*, 2006]. The origin and evolution of the Klondike arc is interpreted to document the closure of a marginal ocean basin, the Slide Mountain ocean, and tectonic transport of the Yukon-Tanana terrane toward western North America. One of the better known aspects of the pericratonic arcs, including the Yukon-Tanana terrane, is the presence of Permian rocks with marine fossils of the "McCloud belt" biogeographic province that are distinct from coeval fauna of the ancestral North American margin [*Miller*, 1987; *Nelson et al.*, 2006]. These fossils have greatly influenced ideas on Permian terrane transport and rates of plate convergence, implying that flare-up of the Klondike arc commenced 2000–3000 km west of the North American craton at a more southerly latitude than today [*Belasky et al.*, 2002; *Stevens and Belasky*, 2009]. However, the actual width of the Slide Mountain ocean during the Permian remains poorly defined because the duration of Klondike arc magmatism and timing of arc-continent collision have been uncertain. Using the available geological data, *Nelson et al.* [2006] proposed that accretion of the Yukon-Tanana terrane along the ancestral North American margin began by Late Permian-Early Triassic time, analogous to the arc-continent collisional model for the Sonoman orogeny. An important prediction of their model is that Triassic clastic strata in the northern Cordillera comprise accretion-related foreland basin and post-accretion overlap assemblage deposits.

[6] In this article, we provide new evidence that supports Late Permian arc-continent collision and accretion of the Yukon-Tanana terrane along the ancestral North American continental margin of northwestern Canada. We herein name this event the Klondike orogeny. Our study begins with determining the U-Pb crystallization ages of zircon and monazite from Permian plutonic rocks in the Klondike District of western Yukon, the type area for the Klondike arc. These data constrain the duration of Klondike arc magmatism, maximum width of the Slide Mountain ocean, and timing of collision-related metamorphism and deformation in the Yukon-Tanana terrane. Detrital zircon U-Pb geochronology is used to examine the Triassic sedimentary record of orogeny and crustal reworking along the ancestral North American margin. This is an appropriate method for testing the model of *Nelson et al.* [2006] because such provenance analysis is a reliable tool for evaluating the source and evolution of sedimentary basins [e.g., *Fedo et al.*, 2003; *Link et al.*, 2005; *Cawood et al.*, 2007]. The data lead us to propose a modified tectonic model for the Cordilleran orogen that includes new ideas into the apparent synchroneity of Late Permian-Early Triassic orogenesis, as well as subsequent Triassic-Jurassic arc magmatism, along much of the length of western North America. This synchroneity may reflect major plate boundary reorganizations related to assembly of Pangaea. Our study demonstrates the utility of geochrono-

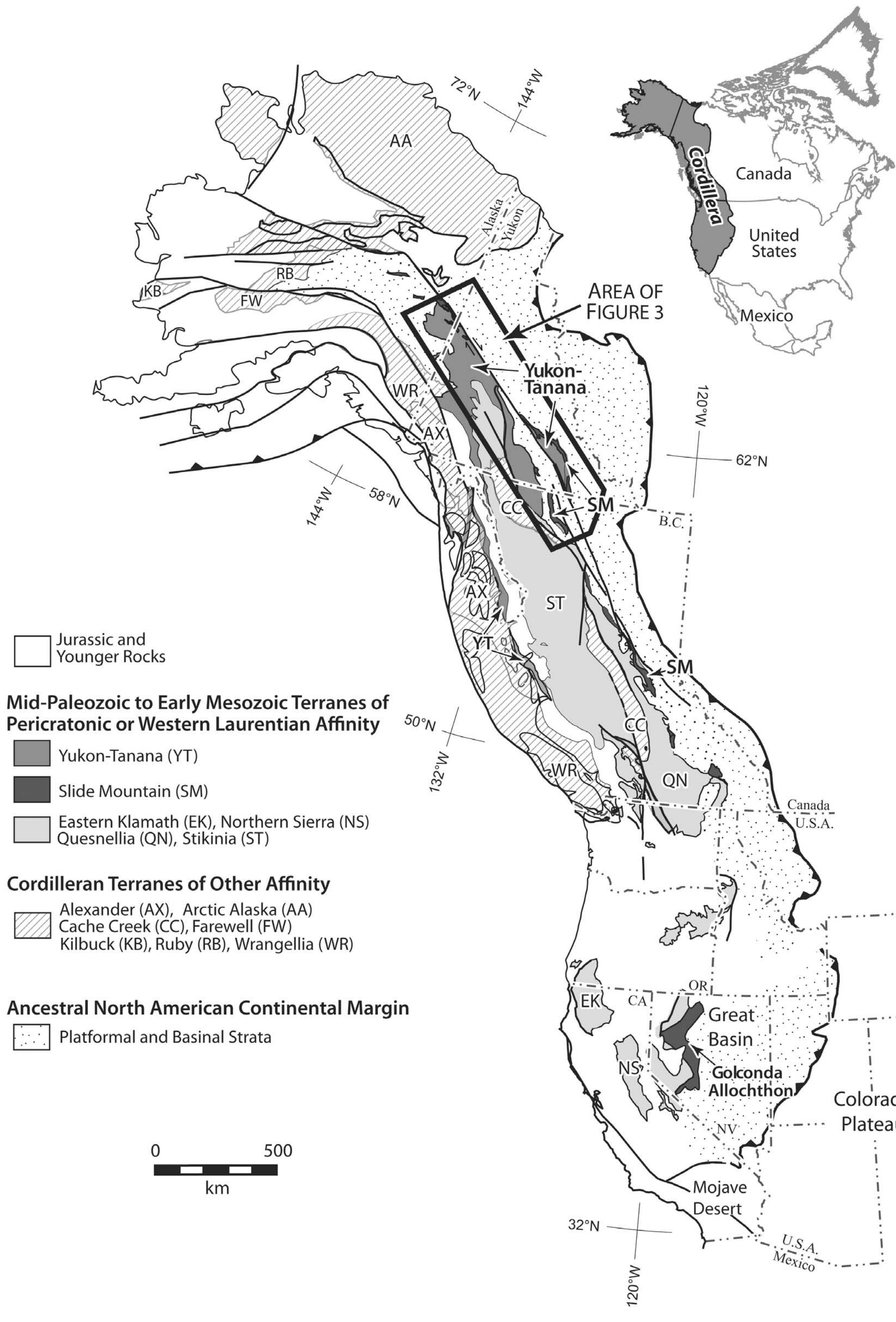

Figure 1. Simplified terrane map of the North American Cordillera. Terranes are grouped according to their affinity or origins. The location of Figure 3 is outlined by the black lined polygon in the northern Cordillera. Modified with permission from work by *Colpron and Nelson* [2009]. Abbreviations: BC – British Columbia, CA – California, NV – Nevada, OR – Oregon, U.S.A. – United States of America.

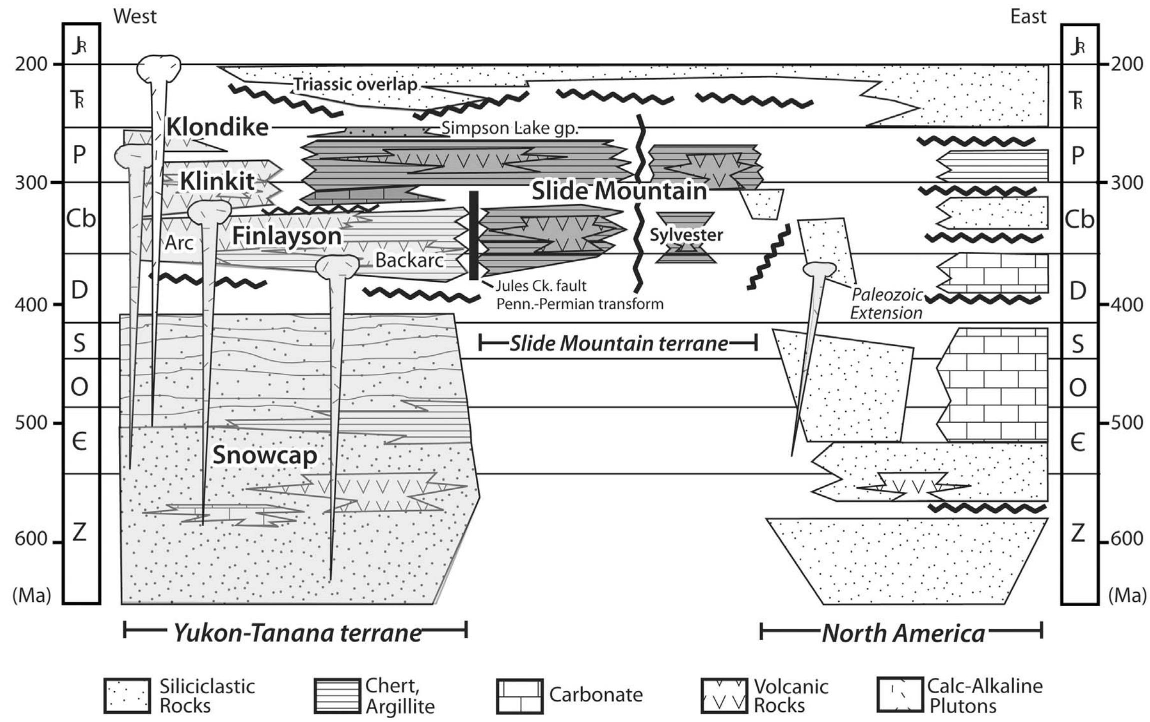

Figure 2. Schematic tectonostratigraphic relationships in the northern Canadian Cordillera. The North American geology on the right-hand side of the diagram is constructed primarily from relationships in southeastern British Columbia [see *Colpron et al.*, 2007]; the left-hand side is based on mapping of the Yukon-Tanana and Slide Mountain terranes in northern British Columbia and Yukon [see *Nelson et al.*, 2006]. Modified from work by *Colpron et al.* [2007].

logical investigations that focus on understanding the timing of tectonothermal events in ancient orogens.

2. Geological Framework

2.1. Yukon-Tanana and Slide Mountain Terranes

[7] The Yukon-Tanana and Slide Mountain terranes occupy an important position at the northern terminus of the Cordilleran orogen in northwestern Canada, lying between in-place (autochthonous) or slightly displaced (parautochthonous) strata of the ancestral North American continental margin to the northeast and far-traveled terranes to the southwest [*Mortensen*, 1992; *Monger and Nokelberg*, 1996]. Although the Yukon-Tanana and Slide Mountain terranes share some geological affinities with northwestern Laurentia, their mid- to late Paleozoic history differs substantially from that of the adjacent continental margin (Figure 2). The tectonostratigraphic framework of the northern Cordillera defines the Yukon-Tanana terrane as a composite of four tectonic assemblages of regional extent and significance [*Colpron et al.*, 2006]. The oldest unit of the Yukon-Tanana terrane, the pre-Late Devonian Snowcap assemblage (Figure 2), is a continental margin succession composed of metasedimentary and metavolcanic rocks. The lithological and isotopic compositions of Snowcap assemblage metaclastic strata suggest a continental derivation similar to that of northwestern Laurentia. For example, Snowcap assemblage quartzite yields Paleoproterozoic and Archean detrital zircons with ages that cluster at 1870, 2080, 2380, and 2720 Ma [*Piercey and Colpron*, 2009], comparable to the Laurentian miogeoclinal reference frame for northern British Columbia [*Gehrels and Ross*, 1998; *Gehrels*, 2000]. The Snowcap assemblage is overlain and intruded by Devonian to Permian arc sequences of the Finlayson, Klinkit, and Klondike assemblages (Figure 2). The Slide Mountain assemblage of the Slide Mountain terrane (Figure 2) consists of oceanic chert, argillite, and mafic volcanic rocks that are coeval with these arc sequences [*Colpron et al.*, 2006].

[8] The Yukon-Tanana terrane probably formed as a distal portion of western North America that rifted off in mid-Paleozoic time, subsequently becoming the nucleus upon which magmatic arcs of the Finlayson, Klinkit, and Klondike assemblages were built [*Nelson et al.*, 2006]. The tectonic development of the Yukon-Tanana terrane was most likely connected to the onset of subduction along the length of western Laurentia during the Middle Devonian [*Rubin et al.*, 1990; *Colpron and Nelson*, 2009]. Initiation of subduction was closely followed by rollback of the downgoing slab, generating widespread magmatism and syngenetic sulfide exhalation in the extending backarc region [*Piercey et al.*, 2004]. The Yukon-Tanana terrane detached from western North America during the latest Devonian-Early Mississippian formation of the Slide Mountain ocean [*Nelson*, 1993]. Persistent east-dipping subduction and growth of the Slide Mountain ocean from Early Mississippian to Early Permian time apparently allowed the Yukon-Tanana terrane to migrate some distance away from western North America. However, by the Early to Middle Permian, the geodynamic setting changed when the polarity of subduction reversed and Slide Mountain ocean lithosphere began to be consumed

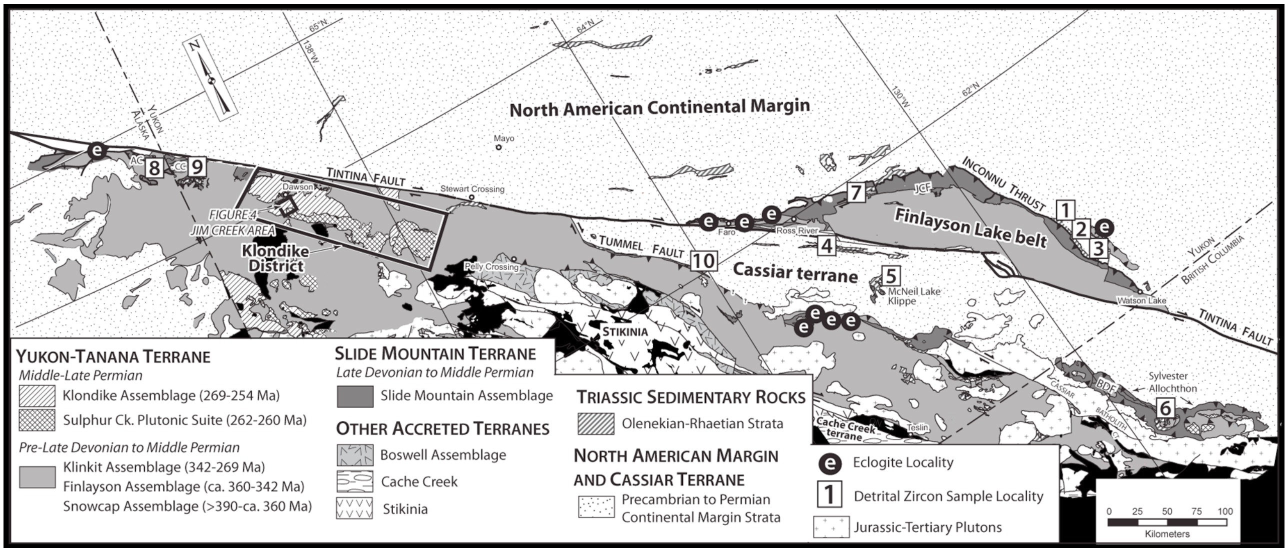

Figure 3. Simplified geological and terrane map of the northern Canadian and Alaskan Cordillera. Detrital zircon sample localities 1–10 are featured in white squares from eastern Alaska to northern British Columbia. The location of Figure 4 is outlined by the black square in the Klondike District of western Yukon. Abbreviations: AC – American Creek ophiolite, BDF – Blue Dome fault, CC – Clinton Creek, JCF – Jules Creek fault, QN – Quesnellia. Modified from *Colpron et al.* [2006].

[*Mortensen*, 1992; *Nelson et al.*, 2006]. Magmatic rocks of the Klondike arc and a paired belt of eclogite and blueschist exposed along the eastern side of the Yukon-Tanana terrane (Figure 3) record this subduction flip. Eclogite and blueschist yield U-Pb zircon and $^{40}Ar/^{39}Ar$ mica ages from 266 to 269 Ma and 240–274 Ma, respectively [*Creaser et al.*, 1997; *Erdmer et al.*, 1998; *Fallas et al.*, 1998]. Permian eclogite bodies have basaltic protoliths with mid-ocean ridge (MORB) to within-plate geochemical affinities [*Creaser et al.*, 1999], consistent with derivation from Slide Mountain ocean crust. Permian conglomerate with clasts of coeval blueschist, eclogite, and volcanic rocks of the Simpson Lake group (Figure 2) comprise remnants of the Klondike forearc in southeastern Yukon [*Murphy et al.*, 2006].

[9] Statistical similarity coefficients for fusulinid and rugose coral faunas in the North American Cordillera suggest that at least some of the pericratonic arc terranes were situated 2000–3000 km offshore of cratonal North America during the Early to Middle Permian [*Belasky et al.*, 2002; *Stevens and Belasky*, 2009]. The Permian McCloud Limestone on the eastern Klamath terrane of northern California contains one of the defining fusulinid genera of the pericratonic biogeographic province, and *Miller* [1987] introduced the name “McCloud belt” to describe the known terranes associated with these faunas. Autochthonous occurrences of McCloud belt fusulinid species are recognized at paleoequatorial latitudes in west Texas, implying a more southerly latitude for the pericratonic terranes during the Permian [*Stevens and Belasky*, 2009]. The Yukon-Tanana terrane may have migrated seaward and southward by 3000 km from Devonian to Middle Permian time, requiring sinistral motion with respect to North America that averages slightly more than 2 cm/yr for 130 m.y. [*Colpron and Nelson*, 2009].

[10] Paleomagnetic constraints on the transport history of the Yukon-Tanana terrane are generally inferred from data collected from the Slide Mountain terrane. In northern British Columbia, paleomagnetic data from Pennsylvanian-Permian red chert in fault slices of Slide Mountain assemblage within the Sylvester allochthon (Figure 3) suggest a post-Permian latitudinal shift of ~20° northward with respect to the North America craton [*Richards et al.*, 1993]. The Sylvester allochthon itself is an imbricated stack of allochthons comprised of the Slide Mountain, Yukon-Tanana, and Quesnellia terranes [*Nelson*, 1993]. Klinkit assemblage limestone containing McCloud fusulinid fauna occurs in the Sylvester allochthon, in broad agreement with a more southerly location for the Yukon-Tanana terrane during the late Paleozoic, as suggested by paleomagnetic studies.

2.2. Key Tectonic Boundaries and Relations of the Northern Cordillera

[11] The structural setting of the northern Cordillera provides the best context in which to understand the geological relationships between the pericratonic terranes and adjacent North American margin, as well as the rationale for selecting detrital zircon sample locations. The Yukon-Tanana and Slide Mountain terranes are notably dissected by the Tintina fault (Figure 3), a prominent transcurrent structure in the northern Cordillera that has accommodated ~430 km of dextral displacement since the Eocene [*Gabrielse*, 1985; *Gabrielse et al.*, 2006]. The Finlayson Lake belt (Figure 3) is an offset block of the Yukon-Tanana and Slide Mountain terranes that occurs to the northeast of the Tintina fault in southeastern Yukon. The eastern margin of the Finlayson Lake belt is delineated by the pre-mid-Cretaceous Inconnu thrust (Figure 3), a major fault that places the Slide Mountain terrane on top of ancestral North America [*Murphy et al.*, 2006]. Southwest of the Tintina fault in central Yukon, the Tummel fault (Figure 3) is the primary structure that juxtaposes the Yukon-Tanana and Slide Mountain terranes against North American continental margin rocks of the para-utochthonous Cassiar terrane [*Colpron et al.*, 2005]. Faults

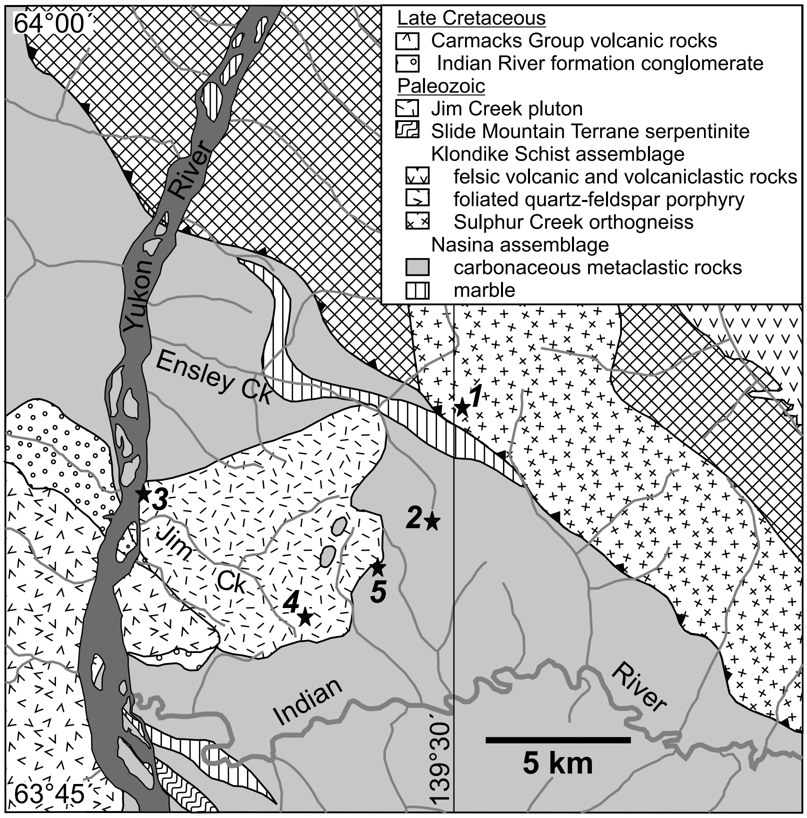

Figure 4. Bedrock geological map of the Jim Creek area, Klondike District, western Yukon. Black stars displayed on the map indicate the locations of the five intrusive rock samples analyzed in this study. Nasina assemblage is local equivalent to Finlayson Assemblage displayed in Figure 2. Abbreviation: Ck. – Creek.

equivalent to the Inconnu thrust are observed along the length of the Cassiar terrane, forming the boundaries between allochthonous terranes and North American assemblages in several klippen. In some areas, such as the Sylvester allochthon of northern British Columbia and McNeil Lake klippe of southern Yukon (Figure 3), the Slide Mountain terrane comprises the immediate hanging wall panel above a master thrust fault [*Nelson and Friedman*, 2004; *Nelson et al.*, 2006]. Klippen of Slide Mountain terrane are also imbricated with Yukon-Tanana terrane southwest of the Tintina fault along the Alaska-Yukon border, at the American Creek ophiolite and Clinton Creek complex (Figure 3).

2.3. Permian Record of Magmatism and Tectonism on the Yukon-Tanana Terrane in Western Yukon

[12] The record of Permian arc magmatism related to closure of the Slide Mountain ocean is well preserved in western Yukon, especially in the Klondike District (Figures 3 and 4), which is the type area for the Klondike assemblage [*Mortensen*, 1990, 1996; *Colpron et al.*, 2006]. The Klondike assemblage in this area comprises mafic to felsic metavolcanic rocks, as well as deformed subvolcanic and plutonic equivalents of the felsic units. This includes the Sulphur Creek orthogneiss (Figure 4), a large body of deformed biotite quartz monzonite from which a U-Pb zircon age of 262.4 ± 2.2 Ma was reported previously [*Mortensen*, 1990]. Regional mapping [*Mortensen*, 1990, 1996; *MacKenzie et al.*, 2008a, 2008b] has shown that the Klondike assemblage in the western Klondike District, including the Sulphur Creek orthogneiss, are in structural contact with underlying carbonaceous metaclastic rocks of the Nasina assemblage (*local name of the Finlayson assemblage*), which are known to be ~360 Ma based on U-Pb zircon ages for interlayered felsic metatuff units (J. K. Mortensen, unpublished data, 2009).

[13] Rock units in this area preserve a complex structural history, including at least five discrete deformation events (D1–D5) [*MacKenzie et al.*, 2008a, 2008b]. The two earliest of these events (D1 and D2) produced the typically flat-lying to shallowly dipping recrystallization fabrics (pervasive F2 and only rarely preserved F1) [*MacKenzie et al.*, 2008a, 2010] that characterize most of the Yukon-Tanana terrane in western Yukon. These early ductile deformation events were associated with regional metamorphism at middle greenschist to lower amphibolite facies, and affected all components of the Klondike and Nasina assemblages. Rock units of the Snowcap assemblage farther to the southwest locally record evidence of an even older (pre-D1; latest Devonian to Early Mississippian) metamorphic event, based on the presence of metamorphic titanite dated at ~365–350 Ma [*Berman et al.*, 2007]. The D1 and D2 events that affected the Klondike assemblage may be no older than late Paleozoic, as hints of a Late Permian metamorphic event are given by ~259 Ma metamorphic rims on detrital zircons from sample of Snowcap assemblage schist [*Villeneuve et al.*, 2003]. The pervasive D1 and D2 deformation in western Yukon are thought to have resulted from deformation in the hinterland (upper plate) of the Yukon-Tanana terrane-Laurentia collisional orogen.

[14] Metamorphic mica and hornblende from throughout much of the Yukon-Tanana terrane in western Yukon give Early and Middle Jurassic $^{40}Ar/^{39}Ar$ ages that are interpreted to record broad post-tectonic regional uplift and exhumation [*Villeneuve et al.*, 2003; *Berman et al.*, 2007]. This late cooling history has made the timing of the dominant early deformation and metamorphism in the Yukon-Tanana terrane difficult to decipher.

[15] The most conclusive evidence for the timing of the pervasive D1 and D2 ductile deformation and recrystallization that affected the Yukon-Tanana terrane in western Yukon comes from the vicinity of Jim Creek in the western part of the Klondike District (Figures 3 and 4). In this area the Sulphur Creek orthogneiss is in structural (thrust?) contact with lower amphibolite facies (garnet grade) carbonaceous schist and quartzite of the Nasina assemblage. A ~15 m thick band of strongly foliated quartz monzonite that is interpreted to be a deformed sill is contained within the Nasina assemblage (Figure 4), and the Nasina metaclastic rocks and the foliated sill contain both the F1 and F2 deformation fabrics. The Nasina assemblage has been intruded by a body of massive, post-tectonic biotite (±garnet) quartz monzonite referred to informally as the Jim Creek pluton (Figure 4). Contacts between the pluton and the Nasina wall rocks are sharp, and undeformed dikes of the pluton cut Nasina units along its eastern boundary. Angular xenoliths of Nasina quartzite containing both the F1 and F2 fabrics occur within the marginal phase of the intrusion. The crystallization ages of the Sulphur Creek orthogneiss, the deformed granitic sill within the Nasina, and the Jim Creek pluton itself, therefore bracket the timing of the F1 and F2 foliations in this area, and, by extension, for the entire Yukon-Tanana terrane in western Yukon.

2.4. Triassic Stratigraphic Assemblages in the Northern Cordillera

[16] The record of Triassic marine sedimentation in the northern Cordillera is preserved as two stratigraphic assemblages that vary in terms of depositional age and geographic location. To the east of the Inconnu thrust and its equivalents, an Early to Middle Triassic assemblage composed of Olenekian to late Ladinian (251–235 Ma; Triassic time scale of *Mundil et al.* [2010]) muscovite-bearing sandstone, shale, and limestone occurs in depositional contact with Devonian to Middle Permian strata of the ancestral North American continental margin, including the Cassiar terrane (Figure 2). There are no contemporaneous strata observed to the west of the Inconnu thrust. Using the tectonic model of *Nelson et al.* [2006], the age and restricted location of the Olenekian to late Ladinian strata implies their genesis is linked to foreland basin development to the east of a Late Permian-Early Triassic collisional suture. Late Triassic strata in the northern Cordillera comprise a regionally extensive early Carnian to Rhaetian (235–200 Ma) assemblage of micaceous sandstone, shale, and limestone that overlies Paleozoic rocks of the Yukon-Tanana and Slide Mountain terranes and North American margin (Figure 2). The lithological similarity of Late Triassic rocks on either side of the Inconnu thrust may indicate the presence of an overlap assemblage deposited after Late Permian-Early Triassic collisional orogenesis [*Murphy et al.*, 2006].

[17] The composition and tectonic setting of Triassic continental margin rocks in Yukon were first constrained by *Beranek et al.* [2010a]. At the type section of the Olenekian Jones Lake Formation along the Yukon-Northwest Territories border, ~200 km northeast of the Inconnu thrust, a basal sandstone unit yielded Devono-Mississippian (360 ± 35 Ma) detrital muscovite and a single Early Mississippian (338 Ma) detrital zircon grain. Olenekian shale samples from the type section have elevated Cr, Ni, and Co values relative to the underlying Paleozoic stratigraphy, suggesting at least partial derivation from ferromagnesian, mafic source rocks. These compositional data are consistent with Paleozoic rocks of the Yukon-Tanana and Slide Mountain terranes being a partial source for Jones Lake Formation strata [*Beranek et al.*, 2010a], although systematic detrital zircon studies are required to evaluate the provenance of Triassic strata in the northern Cordillera. Such provenance analysis is feasible because the U-Pb zircon age signatures of Cordilleran terranes and Laurentian strata are generally well known.

3. U-Pb Geochronology

3.1. Analytical Methods

[18] Zircons were separated from samples of intrusive and sedimentary rocks using conventional crushing, grinding, wet shaking table, heavy liquid, and magnetic separation methods. Conventional ID-TIMS (isotope dilution-thermal ionization mass spectrometry) U-Pb methods on air-abraded, multigrain zircon fractions, and unabraded monazite fractions, were employed initially to date the intrusive rocks in this study. The ID-TIMS methods used are described by *Mortensen et al.* [2008] and the analytical results and coordinates for sample locations are given in the auxiliary material (Data Set S1).[1] Laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) methods, as described by *Tafti et al.* [2009], were subsequently applied to zircons from the original ID-TIMS work in order to resolve complex U-Pb systematics. Analytical data from the LA-ICP-MS study are reported in the auxiliary material (Data Set S2). Assigned ages for samples dated using LA-ICP-MS are based on a weighted mean of $^{206}Pb/^{238}U$ ages.

[19] Analytical results, methodology, and sample location coordinates for the detrital zircon studies are available in the auxiliary material (Data Set S3). The LA-ICP-MS methods follow those of *Beranek et al.* [2010b]. The detrital zircon ages are reported as three age divisions that correspond to eras of the geological time scale, which are also significant in terms of sediment provenance in the northern Cordillera. Mesozoic to mid-Paleozoic (*Mz – mPz*) detrital zircons ranging in age from 200 to 360 Ma are a tracer for magmatic rocks of the Yukon-Tanana and related terranes [*Mortensen*, 1992]. Mid-Paleozoic to late Precambrian (*mPz – lPc*) zircons represented by 360–700 Ma age groups are most typical of Mississippian to Triassic continental margin strata of northwestern Laurentia [*Miller et al.*, 2006; *Beranek et al.*, 2010a, 2010b], although 360–390 Ma magmatic rocks are known to the Yukon-Tanana terrane. Late Precambrian and older ages (*Pc*) from 1000 to 2700 Ma represent multicycle

[1] Auxiliary materials are available at ftp://ftp.agu.org/apend/tc/2010tc002849.

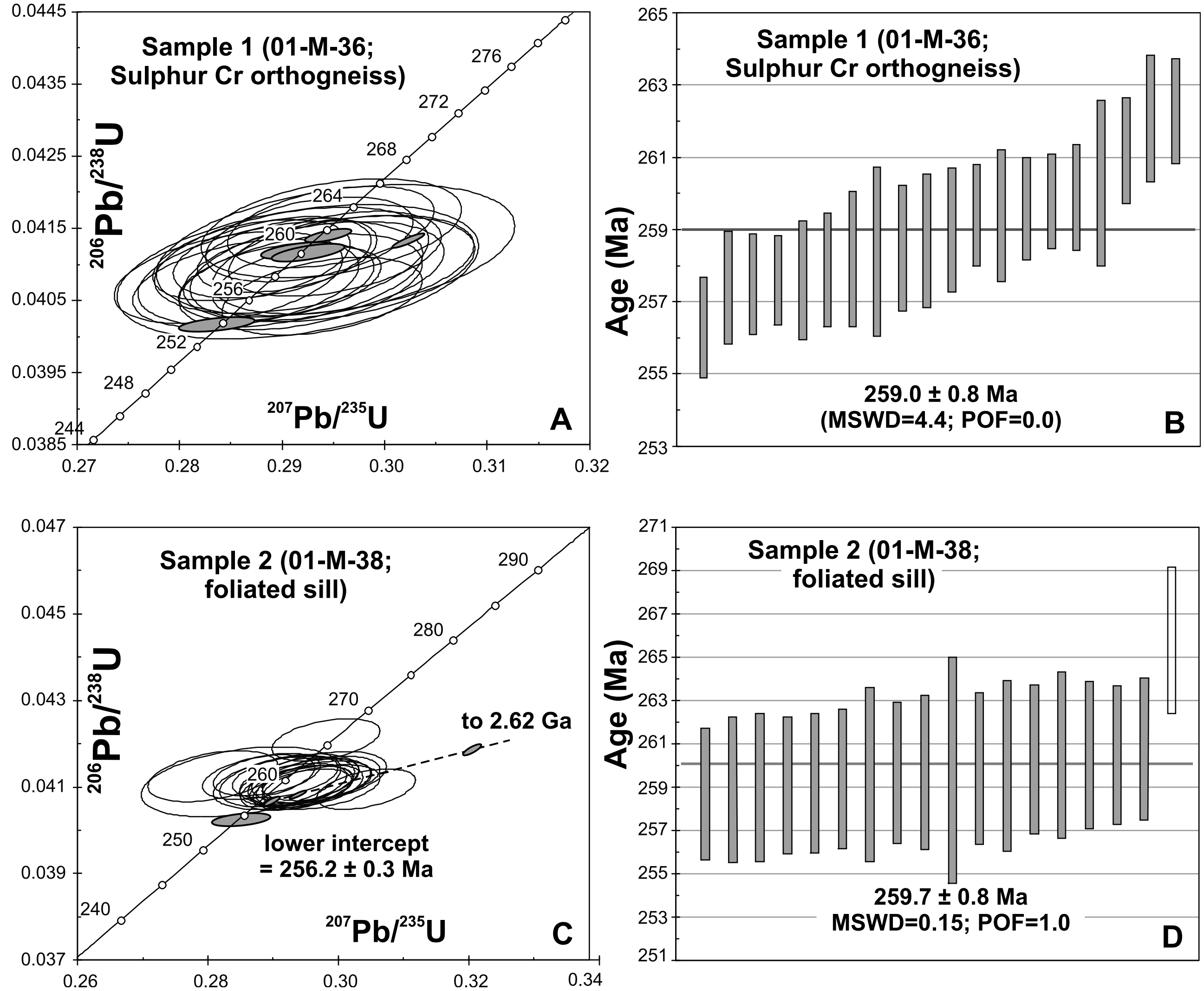

Figure 5. Conventional (a, c) ID-TIMS and (b, d) LA-ICP-MS analytical results for zircons from samples of the Sulphur Creek orthogneiss (Sample 1) and a foliated granite sill (Sample 2). ID-TIMS analyses in Figures 5a and 5c are shaded and LA-ICP-MS analyses are shown as open ellipses. Analyses that were used for calculation of the weighted average $^{206}Pb/^{238}U$ age for LA-ICP-MS analyses are shaded. All errors are shown at the 2-sigma level. Abbreviations: MSWD – Mean Square Weighted Deviation, POF – Probability of Fit.

detrital zircons that are originally derived from Proterozoic and Archean crystalline rocks of various cratonal provinces [e.g., *Gehrels and Ross*, 1998] or the Snowcap assemblage [*Piercey and Colpron*, 2009].

3.2. Permian Intrusive Rocks

[20] Two samples of deformed felsic intrusive rock from the Klondike District were dated. Sample 1 was from the Sulphur Creek orthogneiss (Figure 4), which is coeval and comagmatic with metamorphosed hypabyssal and volcanic rocks of the Klondike assemblage in its type area, and is therefore representative of the Late Permian arc that was constructed on the Yukon-Tanana terrane during closure of the Slide Mountain ocean. Sample 2 is from a foliated granitic sill within the structurally underlying Nasina assemblage (Figure 4). Samples 3 and 4 are from biotite and garnet-biotite quartz monzonite, respectively, of the Jim Creek pluton (Figure 4). Sample 5 is from a dike related to the Jim Creek pluton that intrudes the Nasina assemblage near its eastern margin (Figure 4).

[21] The sample of Sulphur Creek orthogneiss yielded abundant zircons that mainly comprised stubby to elongate square prisms with simple terminations. Inherited cores were present in a small proportion of the grains. Five strongly abraded multigrain fractions of zircon were analyzed initially (Data Set S1). Four of these gave concordant analyses (Figure 5a). Two analyses (Figures 5c and 5d) are overlapping with a weighted average $^{206}Pb/^{238}U$ age of 259.9 ± 0.8 Ma. Fraction B gives a slightly older $^{206}Pb/^{238}U$ age of 261.4 ± 0.5 Ma, whereas fraction A gives a younger age of 253.7 ± 0.5 Ma. Twenty zircon grains from this sample were subsequently dated using LA-ICP-MS methods (Figure 5b and Data Set S2). There is some scatter in the data, possibly reflecting minor Pb-loss for some of the grains. A weighted

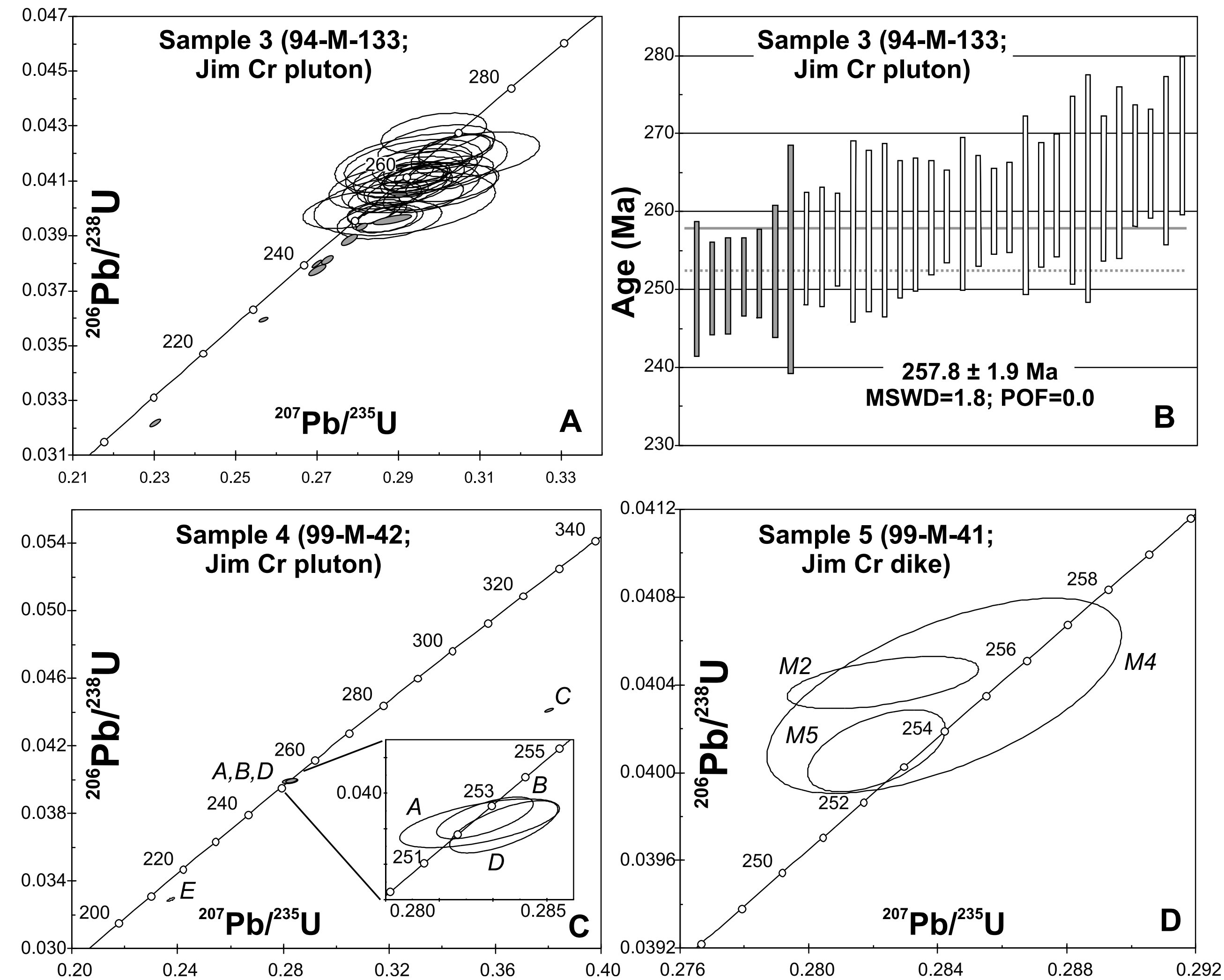

Figure 6. Conventional (a, c, d) ID-TIMS and (b) LA-ICP-MS analytical results for zircons from samples of the Jim Creek pluton. ID-TIMS analyses in Figure 6a are shaded and LA-ICP-MS analyses are shown as open ellipses. Abbreviations: MSWD – Mean Square Weighted Deviation, POF – Probability of Fit.

average $^{206}Pb/^{238}U$ age of all twenty analyses is 259.0 ± 0.8 Ma, with a mean square of weighted deviates (MSWD) of 4.4 and a probability of fit (POF) of 0. In view of the scatter in the LA-ICP-MS data we assign a conservative age estimate of 260.5 ± 1.4 Ma to the sample, based on the entire range of $^{206}Pb/^{238}U$ ages for the three oldest concordant ID-TIMS analyses.

[22] Zircons recovered from Sample 2 (foliated sill in Nasina assemblage) are similar in appearance to those in the previous sample. Again, five fractions of strongly abraded multigrain zircon fractions were analyzed initially (Data Set S1). Four of these define a discordia array (Figure 5c) with calculated lower and upper intercept ages of 256.2 ± 0.3 Ma and 2624 Ma, respectively. A fifth fraction (C) gives a concordant but considerably younger age of 254.2 ± 0.7 Ma. Twenty zircon grains from the sample were analyzed using LA-ICP-MS (Data Set S2). All but one of these give identical $^{206}Pb/^{238}U$ ages; however, three of the analyses are not completely concordant. A weighted average $^{206}Pb/^{238}U$ age for all but one of the concordant LA-ICP-MS analyses is 259.7 ± 0.8 Ma (MSWD = 0.15; POF = 1.0). One analysis gives an older $^{206}Pb/^{238}U$ age of 265.8 ± 0.3 Ma, and is interpreted to be of xenocrystic origin. We interpret the LA-ICP-MS age to be the best estimate of the crystallization age of the sample.

[23] Three samples of the Jim Creek pluton were dated in this study. Ten strongly abraded multigrain zircon fractions from a sample near the western edge of the intrusion (Sample 3, Figure 4) gave very scattered ID-TIMS analyses (Figure 6a and Data Set S2), indicating both substantial post-crystallization Pb-loss and at least a minor amount of inheritance. Thirty-two LA-ICP-MS analyses of zircons from the same sample give a range of $^{206}Pb/^{238}U$ ages with an average of 257.8 ± 1.9 Ma (Figure 6b and Data Set S2). Five multigrain zircon fractions from Sample 4 from the core of the pluton were dated using ID-TIMS methods (Data Set S2). Three strongly abraded fractions give overlapping $^{206}Pb/^{238}U$ ages with an average of 252.5 ± 0.4 Ma (Figure 6c), which is considered to be the best estimate for the crystallization age of the sample. One abraded fraction (C) yields a much older age, indicating the presence of a substantial older inherited zircon component, and an unabraded fraction shows the effects of

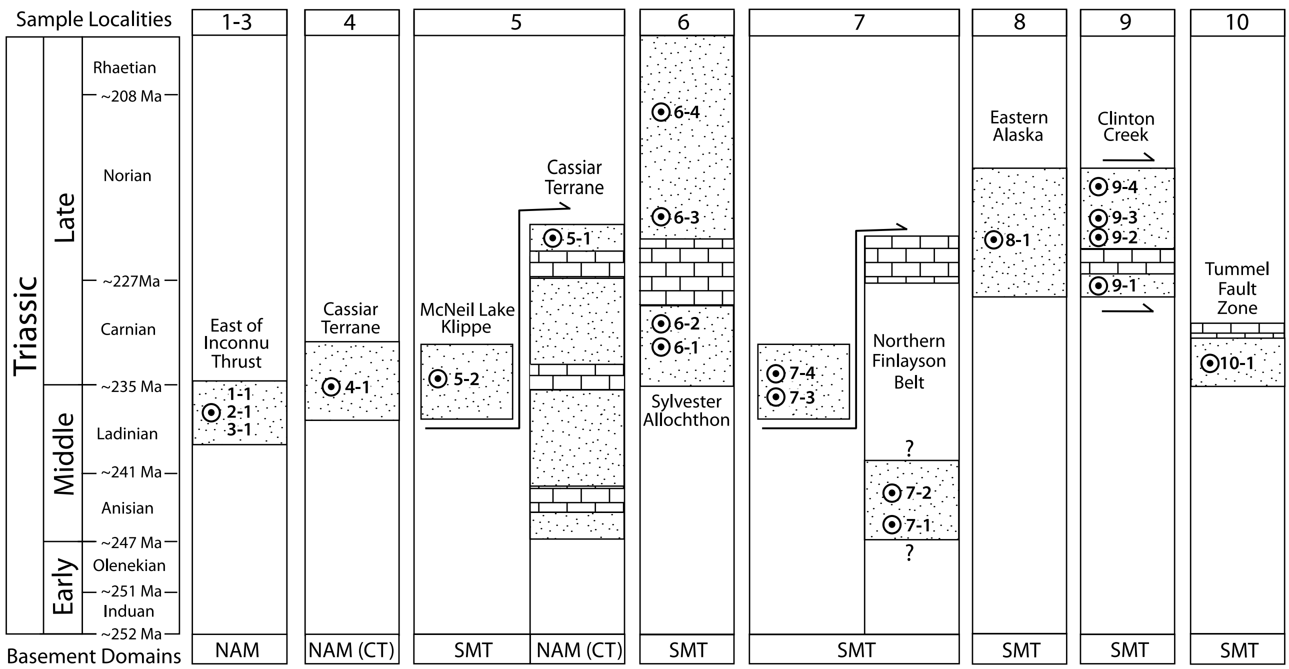

Figure 7. Simplified stratigraphic framework for Triassic detrital zircon sample locations in eastern Alaska, Yukon, and northern British Columbia. The number on the top of each column corresponds to the detrital zircon sample locality indicated in Figure 3. Detrital zircon sample numbers within each stratigraphic column correspond to U-Pb zircon results in Figures 8–11. Lithologic symbols are as defined in Figure 3. Depositional ages are from *Orchard* [2006]. Triassic time scale used is from *Mundil et al.* [2010].

strong post-crystallization Pb-loss. Sample 5, from a dike near the eastern margin of the Jim Creek pluton, yielded abundant zircons, many of which contained visible cloudy cores, as well as monazite. Three unabraded fractions of monazite were analyzed (Data Set S2). The three fractions fall slightly above concordia, presumably reflecting the presence of minor excess ^{206}Pb related to disequilibrium effects (Figure 6d). A weighted average ^{207}Pb/^{235}U age for three monazite fractions of 252.5 ± 1.1 Ma is therefore considered to give the best estimate for the age of the sample.

[24] The age calculated for Sample 3 is somewhat older than that determined for the other two samples of the Jim Creek pluton. Zircons from Sample 3 contain abundant visible inherited cores, and the fact that all of the fractions analyzed by ID-TIMS were free of visible cores but yielded analyses indicating the ubiquitous presence of an inherited zircon component (all measured ^{207}Pb/^{206}Pb ages are > 266 Ma; Data Set S1), suggests that inherited zircon cores and/or xenocrystic zircons are abundant in this sample. The seven analyses that gave the youngest ^{206}Pb/^{238}U age (shaded in Figure 6b), however, have an average age of 251.3 ± 2.5 Ma. This is consistent with the ages obtained for the other two Jim Creek samples, and may indicate that at least some of the grains selected for analysis were primary igneous zircons free of inherited cores. We consider the best estimate for the crystallization age of the Jim Creek pluton to be given by the TIMS age of 252.5 ± 0.4 Ma for sample 4.

[25] The U-Pb zircon age of 262.4 ± 2.2 Ma for the Sulphur Creek orthogneiss reported previously by *Mortensen* [1990] is in good agreement with the age of 260.5 ± 1.4 Ma that we report here for a separate sample. This age is interpreted to give the age of arc magmatism in the Yukon-Tanana terrane during closure of the Slide Mountain ocean. The foliated sill in the Nasina assemblage gives an identical age of 259.7 ± 0.8 Ma. Both of these samples have been affected by both the D1 and D2 deformation events. Two samples of the Jim Creek pluton give identical ages of 252.5 ± 0.4 Ma and 252.5 ± 1.1 Ma. A third sample of the pluton gives more scattered U-Pb zircon ages; however, the results are consistent with a crystallization age similar to that given by the other two samples. The Jim Creek pluton has a strongly peraluminous composition (J. K. Mortensen, unpublished data), suggesting that it is of crustal origin. Zircons from Late Permian arc rocks were likely incorporated into the Jim Creek pluton as xenocrysts.

3.3. Triassic Strata Overlying the North American Continental Margin

3.3.1. East of the Finlayson Lake Belt, Southeastern Yukon (Localities 1–3)

[26] Three samples of fine- to medium-grained, thin- to medium-bedded, micaceous to calcareous sandstone were collected from a belt of late Ladinian marine strata that crops out in the immediate footwall to the Inconnu thrust, east of the Finlayson Lake belt in southeastern Yukon (localities 1–3 in Figures 3 and 7). Late Ladinian rocks of the region are in depositional contact with mid- to late Paleozoic strata of the ancestral North American continental margin [*Mortensen and Murphy*, 2005; *Murphy et al.*, 2006] and locally display paleocurrent indicators suggesting a western source [*Abbott*, 1977]. Conodont age-constrained late Ladinian sandstones were analyzed to test Middle Triassic basin evolution along

the ancestral North American continental margin and potential derivation from Cordilleran terranes that presently crop out west of the Inconnu thrust.

[27] Averaged detrital zircon results from the three Ladinian sandstone samples show a broad distribution in age spectra (Mz-mPz − 15%, mPz-lPc − 45%, Pc − 40%; samples 1-1, 2-1, and 3-1 in Figures 8a–8c). The majority of Mz-mPz detrital zircon ages range from 252 to 357 Ma. Using the Triassic time scale of *Mundil et al.* [2010], the maximum depositional age for each sandstone sample is constrained by Anisian to Ladinian detrital zircons (236 ± 5 Ma, 236 ± 6 Ma, 243 ± 3 Ma, respectively; Figures 8a–8c).

3.3.2. Ross River Area, Cassiar Terrane, South-Central Yukon (Locality 4)

[28] A sample of medium-grained, thin- to medium-bedded calcareous sandstone was selected from the northern Cassiar terrane immediately southwest of the Tintina fault near the town of Ross River, Yukon (locality 4 in Figures 3 and 7). Triassic rocks in this area consist of conodont-bearing late Ladinian to early Carnian calcareous sandstone, shale, and limestone in depositional and faulted contact with Paleozoic continental margin strata [*Tempelman-Kluit*, 1977; *Orchard*, 2006]. This sample was analyzed to constrain the detrital zircon provenance signatures of northern Cassiar terrane strata.

[29] Detrital zircon ages in the sample are widely distributed (Mz-mPz − 12%, mPz-lPc − 20%, Pc − 68%), with the majority of Mz–mPz ages in the range of 294–312 Ma (sample 4-1 in Figure 8d). The youngest detrital zircon in the sample is Early Permian in age (294 ± 13 Ma; Figure 8d).

3.3.3. McNeil Lake Area, Cassiar Terrane, South-Central Yukon (Locality 5)

[30] A sample of coarse-grained, medium- to thick-bedded muscovite-bearing sandstone was collected at the top of an Anisian to Norian succession in the McNeil Lake area of the Cassiar terrane in south-central Yukon (locality 5 in Figures 3 and 7). Middle Permian and older continental margin strata underlie the Triassic succession. The sample of Norian sandstone was selected for detrital zircon geochronology because of its coarse-grained and micaceous nature, which is unique in this part of the Cassiar terrane.

[31] The Norian sandstone sample has a diverse detrital zircon age distribution (Mz-mPz − 13%, mPz-lPc − 26%, Pc − 60%), with the youngest components of the Mz-mPz group typically ranging from 240 to 267 Ma (sample 5-1 in Figure 8e). The maximum depositional age is constrained by early Norian (222 ± 3 Ma) detrital zircon (Figure 8e), which is compatible with Norian conodonts at the top of the section [*Orchard*, 2006].

3.4. Triassic Strata Overlying the Slide Mountain Terrane

3.4.1. McNeil Lake Klippe, South-Central Yukon (Locality 5)

[32] Cassiar terrane strata in the McNeil Lake area are structurally overlain by klippen of the Slide Mountain terrane, each of which are locally referred to as the McNeil Lake klippe. The klippe contain relatively undeformed volcanic lithic sandstone, crystal lithic tuff, and rhyolite porphyry, along with highly deformed ribbon chert and calc-silicate rocks [*Gordey*, 1981]. Each of klippe are typically hundreds of meters thick and occupy ~5 km^2. A detrital zircon sample was analyzed from a 100 m-thick lens of coarse-grained volcanic lithic sandstone in apparent thrust-related contact with underlying Triassic strata of the Cassiar terrane and overlying Slide Mountain assemblage chert. The lens has a lateral extent of hundreds of meters, immediately above the location of detrital zircon sample 5-1 (locality 5 in Figures 3 and 7). This sample was collected to understand the crustal affinity of rocks involved in the McNeil Lake klippe.

[33] The volcanic lithic sandstone has a unimodal (Mz-mPz − 99%, Pc − 1%) population defined by 250–270 Ma detrital zircons (sample 5-2 in Figure 9a). The occurrence of Middle Triassic zircon (237 ± 2 Ma) indicates a late Ladinian maximum depositional age for the sample (Figure 9a).

3.4.2. Sylvester Allochthon, Northern British Columbia (Locality 6)

[34] The Sylvester allochthon is an imbricate stack of ophiolitic, island arc, and pericratonic assemblages that together form a large klippe in thrust-related contact with the Cassiar terrane in northern British Columbia (Figure 3). *Nelson* [1993] separated rocks of the Sylvester allochthon into three structural packages (Divisions I, II, III), themselves internally imbricated, which from bottom to top comprise units of the Slide Mountain, Quesnellia, and Yukon-Tanana terranes. Carnian to Rhaetian muscovite-bearing sandstone, shale, and limestone of the Table Mountain formation occupy the highest structural level of Division II in the Sylvester allochthon, in sheared contact with underlying Slide Mountain assemblage units (locality 6 in Figures 3 and 7). The sheared contact is considered to be an unconformity that was reactivated into a decollement [*Nelson and Bradford*, 1988]. *Nelson* [1993] noted that Table Mountain formation rocks are lithologically similar to coeval strata of the Cassiar terrane and Quesnellia in British Columbia, implying all of the Late Triassic rocks were deposited across a collisional suture that linked allochthonous terranes with western North America. We analyzed four samples of fine- to medium-grained micaceous sandstone of the Table Mountain formation to evaluate these proposed stratigraphic ties with the North American margin.

[35] In general, the samples yield similar age spectra (samples 6-1 to 6-4 in Figures 9b–9e). Averaged results for the four samples indicate that ~90% of the detrital zircons are mid-Paleozoic and older (Mz–mPz − 13%, mPz–lPc − 40%, Pc − 47%). The youngest ages typically range from 250 to 350 Ma. The Table Mountain formation samples consistently yield maximum depositional ages based on detrital zircons that are compatible with Late Triassic fossil data (236 ± 2 Ma, 235 ± 2 Ma, 221 ± 4 Ma, 213 ± 2 Ma, respectively).

3.4.3. Northern Finlayson Lake Belt, Southeastern Yukon (Locality 7)

[36] Within the northern Finlayson Lake belt, a tract of Norian and older sandstone, shale, and limestone (locality 7 in Figures 3 and 7) are in depositional contact with highly deformed Slide Mountain assemblage rocks in the hanging wall of the Inconnu thrust [*Murphy et al.*, 2006]. We analyzed samples of coarse-grained, chert lithic sandstone and feldspathic sandstone of uncertain age at the base of the Triassic succession, along with two samples of chert pebble conglomerate that comprise part of an imbricated thrust sheet that structurally overlies Norian limestone. These samples

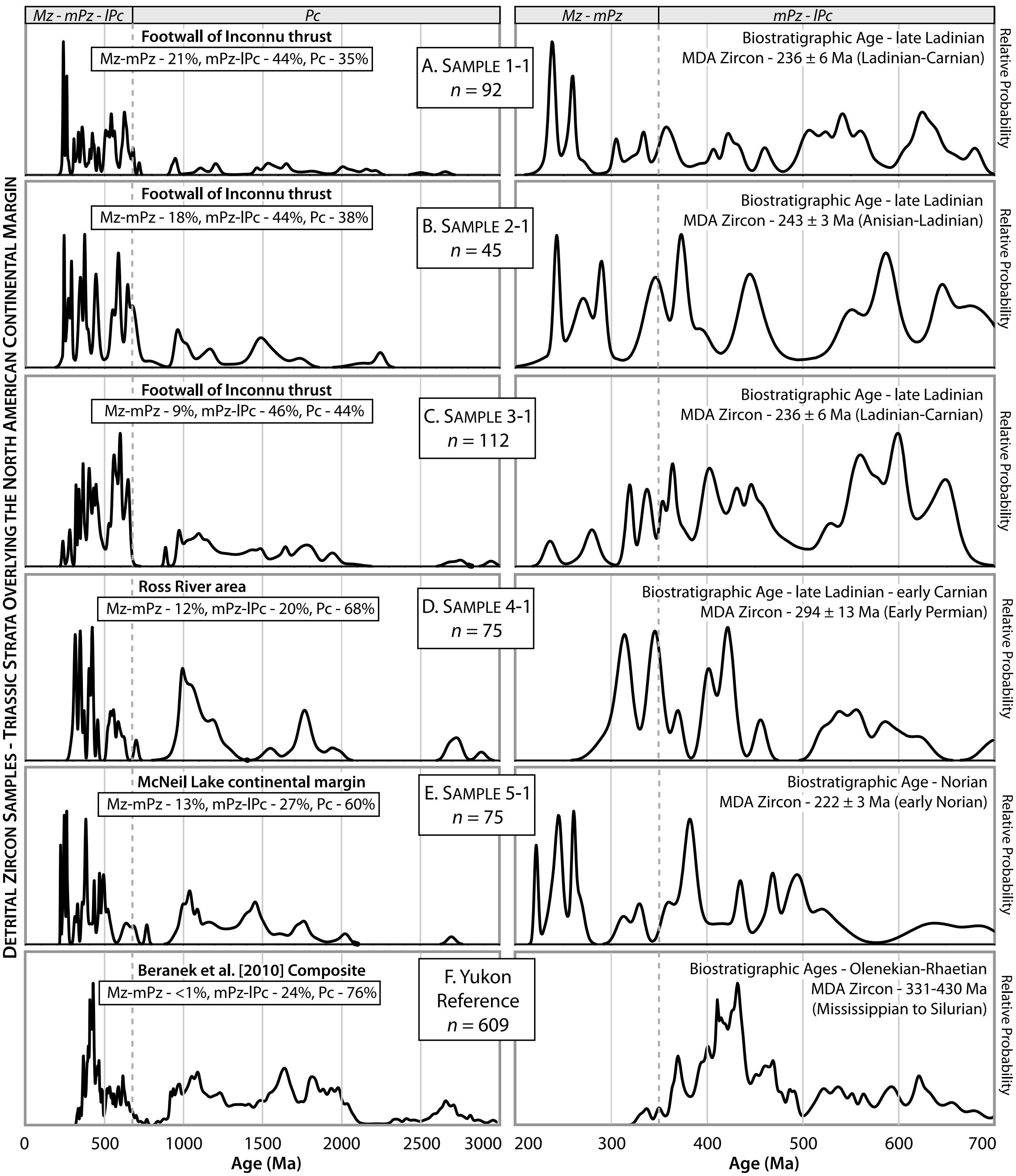

Figure 8. Relative probability plots (0–3000 Ma and 200–700 Ma) displaying LA-ICP-MS detrital zircon ages from Triassic strata overlying the ancestral North American continental margin. (a–c) late Ladinian samples collected at localities 1–3 to the east of the Inconnu thrust in southeastern Yukon; (d) late Ladinian to early Carnian sample collected at locality 4 to the south of Ross River, central Yukon; (e) Norian sample collected at locality 5 in the McNeil Lake area of south-central Yukon; and (f) reference frame for Triassic continental margin in Yukon by *Beranek et al.* [2010a]. Abbreviation: MDA – maximum depositional age of sample derived from the youngest detrital zircon.

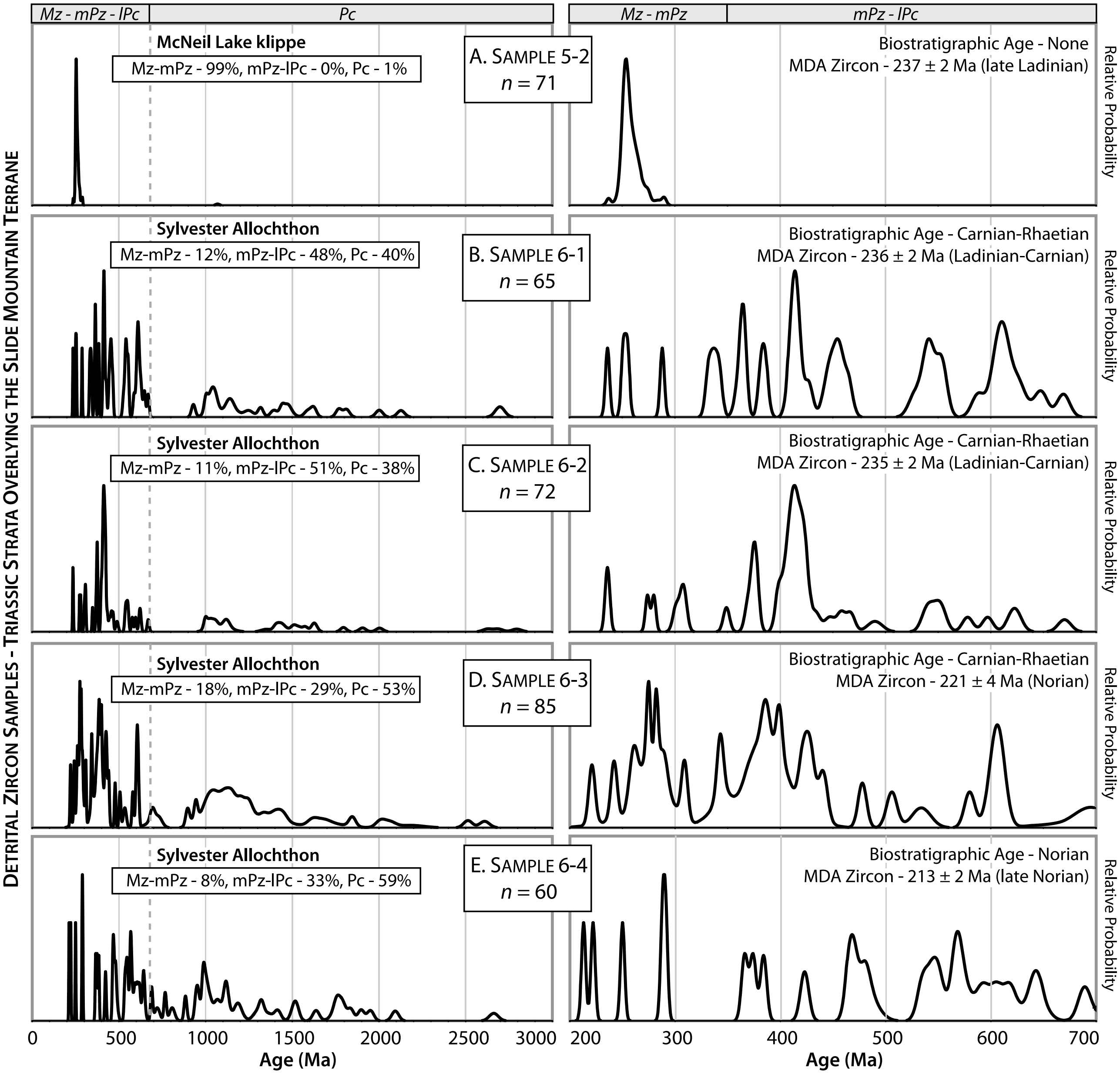

Figure 9. Relative probability plots (0–3000 Ma and 200–700 Ma) displaying LA-ICP-MS detrital zircon ages from Triassic strata overlying the Slide Mountain terrane in south-central Yukon and northern British Columbia. (a) sample of unknown depositional age associated with McNeil Lake klippe at locality 5; and (b–e) Carnian to Rhaetian samples collected from the Table Mountain formation in the Sylvester allochthon. Abbreviation: MDA – maximum depositional age of sample derived from the youngest detrital zircon.

constrain the detrital zircon signatures of Triassic rocks deposited in proximity to the Slide Mountain and Yukon-Tanana terranes immediately west of the trace of the Inconnu thrust.

[37] Averaged results from the four samples illustrate unimodal detrital zircon populations (Mz–mPz − 90%, mPz–lPc − 3%, Pc − 7%), with the majority of grains (254 of 282 analyses) yielding ages that range from 250 to 270 Ma (samples 7-1 to 7-4 in Figures 10a–10d). The composite signature of all samples gives a total of 19 detrital zircon ages at 1112, 1308, ca. 1400–1600, 1723–1779, and 1800–2600 Ma; however, these Precambrian grains are largely obscured in probability plots by younger zircon ages. Middle Triassic detrital zircons occurring in three of the four samples (236 ± 3 Ma, 242 ± 3 Ma, 245 ± 4 Ma) indicate an Anisian-Ladinian maximum depositional age for the succession.

3.4.4. American Creek, Eastern Alaska and Clinton Creek, Western Yukon (Localities 8 and 9)

[38] Late Carnian to middle Norian micaceous sandstone, shale, and limestone occur in faulted and depositional contact with pillowed greenstone, serpentinized peridotite, and metaclastic rocks of the Slide Mountain assemblage along the Yukon-Alaska border, south of the Tintina fault (localities 8 and 9 in Figures 3 and 7). Late Triassic strata in this region have a low metamorphic grade and are not penetratively

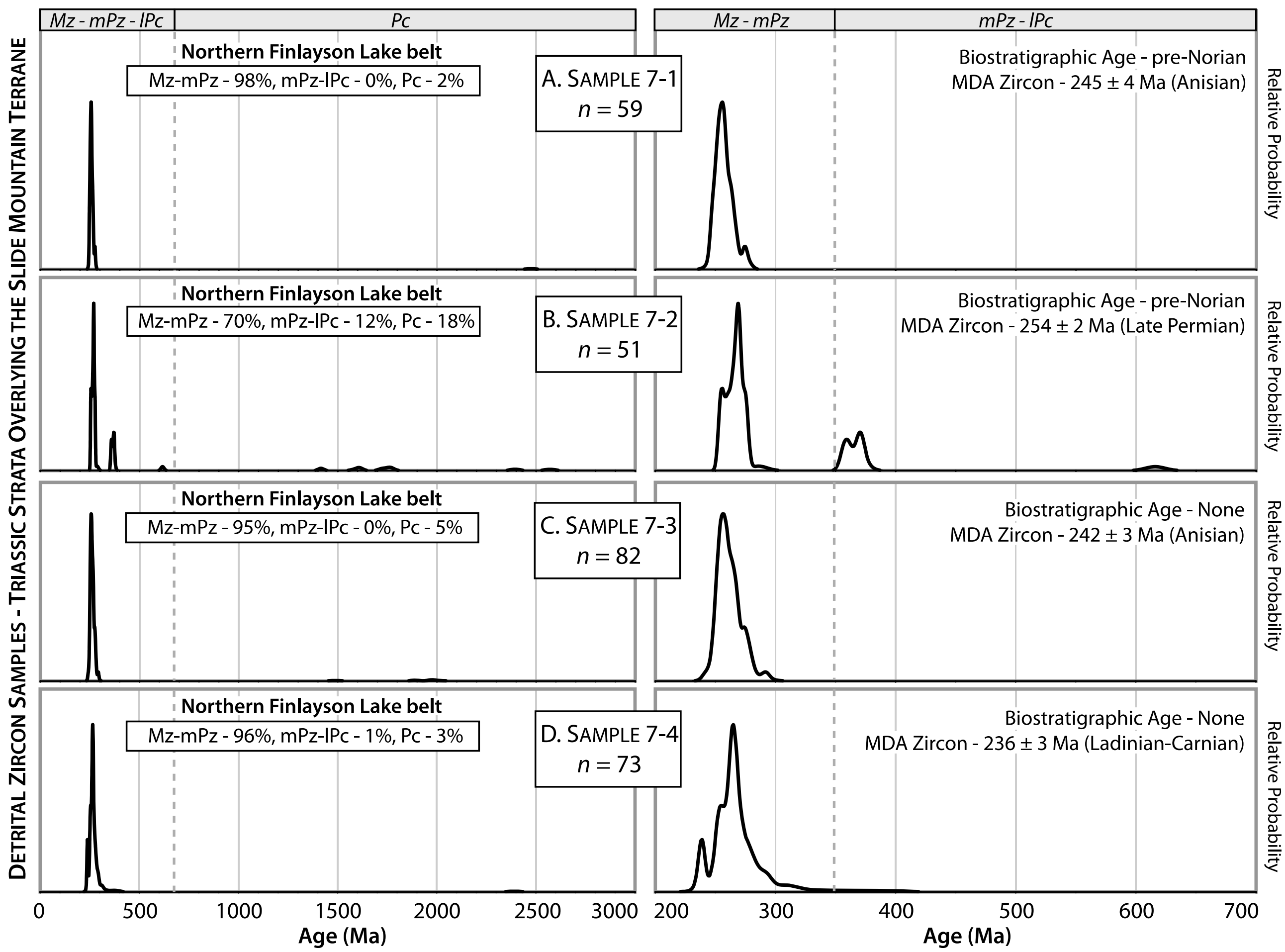

Figure 10. Relative probability plots (0–3000 Ma and 200–700 Ma) displaying LA-ICP-MS detrital zircon ages from Triassic strata overlying the Slide Mountain terrane at locality 7, northern Finlayson Lake belt, southeastern Yukon. (a and b) Samples of unknown depositional age collected at base of pre-Norian succession; (c and d) samples of unknown depositional age collected from imbricate stack of siliciclastic rocks that overlies pre-Norian stratigraphic section in northern Finlayson Lake belt. Abbreviation: MDA – maximum depositional age of sample derived from the youngest detrital zircon.

deformed [*Foster et al.*, 1994; *Dusel-Bacon et al.*, 2006]. We analyzed five samples of conodont age-constrained, fine- to medium-grained, micaceous and calcareous sandstone collected near the American Creek ophiolite in eastern Alaska and within the Clinton Creek complex in western Yukon. Similar to the sampling strategy for coeval strata of the Table Mountain formation, these Late Triassic rocks test the presence of an overlap assemblage deposited over both western North America and deformed rocks of the Slide Mountain terrane.

[39] The results for the five samples are generally similar (samples 8-1, 9-1 to 9-4 in Figures 11a–11e), and averaged values show that detrital zircon components are typically mid-Paleozoic and older (Mz–mPz − 12%, mPz–lPc − 36%, Pc − 52%). Late Permian to Early Mississippian (256–347 Ma) detrital zircon comprises the majority of the youngest components in the Mz-mPz division. Two of the four samples from Clinton Creek contain early Norian (228 ± 4 Ma and 228 ± 2 Ma, respectively) detrital zircons that are in agreement with conodont biostratigraphic control, whereas the youngest grains in the other samples range in age from Mississippian to Permian (Figures 11a–11e).

3.4.5. Tummel Fault Zone, Central Yukon (Locality 10)

[40] The Tummel fault zone is a narrow structural belt in central Yukon that juxtaposes the Yukon-Tanana and Slide Mountain terranes to the west with the North American margin to the east. Triassic strata in the Tummel fault zone occur in faulted and depositional contact with these terranes, including tectonized harzburgite, chert, and mafic volcanic rocks of the Slide Mountain assemblage [*Colpron et al.*, 2005]. We analyzed a sample of fine-grained, thin- to medium-bedded, muscovite-bearing sandstone underlain by Pennsylvanian-Permian chert of the Slide Mountain assemblage to evaluate the provenance of Triassic rocks in the Tummel fault zone (locality 10 in Figure 3).

[41] The sample has a diffuse detrital zircon signature (sample 10-1 in Figure 11f) with an abundance of Precambrian detrital zircons (Mz–mPz − 12%, mPz–lPc − 25%, Pc − 63%). Late Triassic (230 ± 3 Ma) detrital zircon suggests

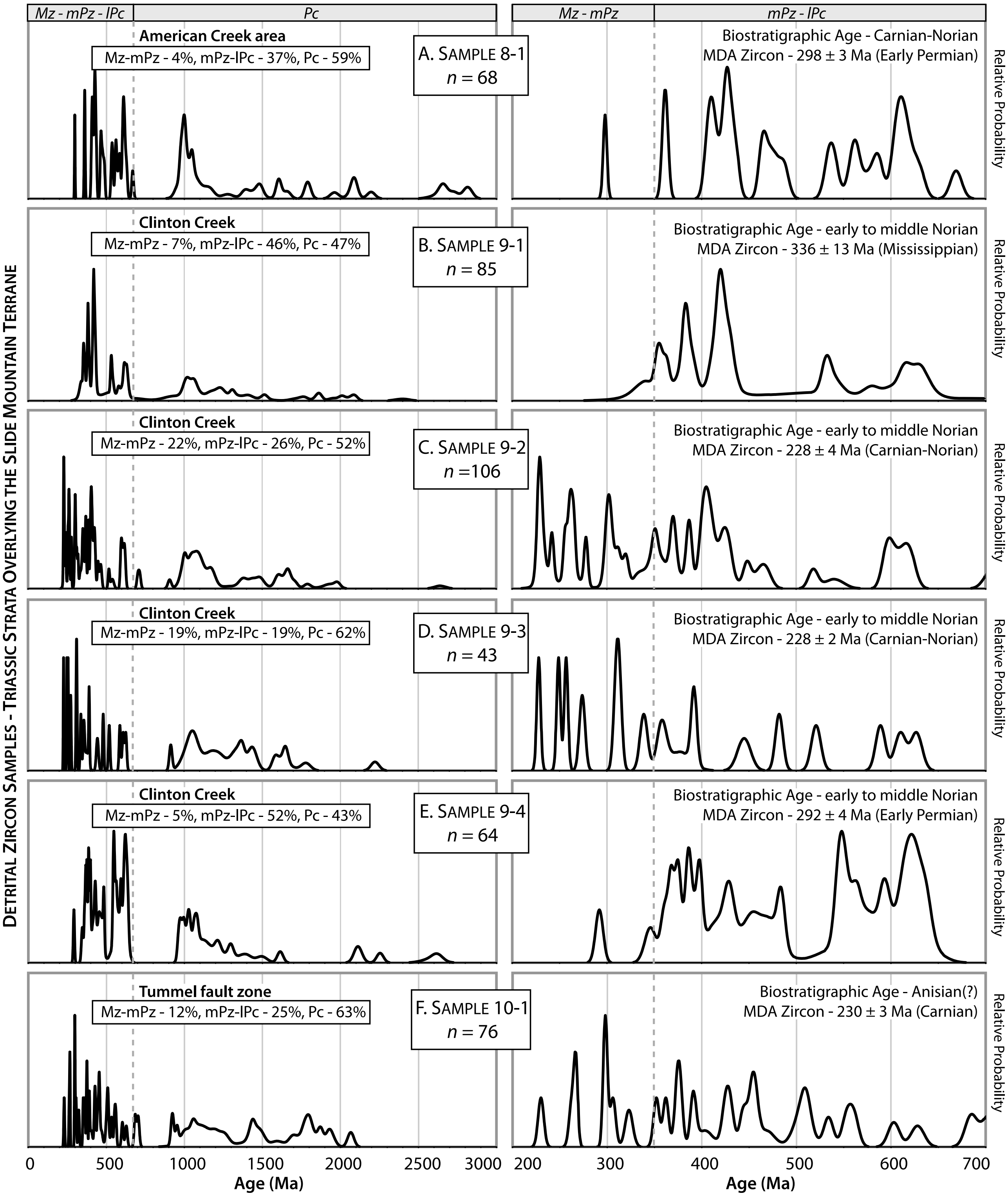

Figure 11. Relative probability plots (0–3000 Ma and 200–700 Ma) displaying LA-ICP-MS detrital zircon ages from Triassic strata overlying the Slide Mountain terrane from eastern Alaska, western Yukon, and central Yukon. (a) Carnian to Norian sample collected near American Creek ophiolite at locality 8; (b–e) Early to Middle Norian samples collected from Clinton Creek complex at locality 9; (f) Anisian to Carnian sample collected from Tummel fault zone at locality 10. Abbreviation: MDA – maximum depositional age of sample derived from the youngest detrital zircon.

a latest Carnian to earliest Norian maximum depositional age for the sample (Figure 11f).

4. Discussion

4.1. Tectonic Setting of Permian Magmatism and the Klondike Orogeny

[42] Geochronological studies of intrusive rocks in the Klondike District provide critical new insights into the magmatic and tectonic evolution of the Yukon-Tanana terrane. We interpret the crystallization age of the Sulphur Creek orthogneiss to indicate that the Slide Mountain ocean was still closing at ~260 Ma, but the intrusion of the post-tectonic Jim Creek pluton at 252.5 Ma signifies the ocean had at least partially closed, and some or all of the Yukon-Tanana terrane had overridden the ancestral North American continental margin. This arc-continent collision produced the D1 and D2 ductile deformation events in the Klondike District and probably generated the parent magmas for the Jim Creek pluton through crustal thickening and anatexis at depth. The earliest timing of accretion of the Yukon-Tanana terrane against western North America, based on the geology and age relations within the hinterland of the arc-continent collision, is therefore bracketed between 260 and 252.5 Ma. Because the Klondike District records the history of Late Permian magmatism, deformation, and metamorphism related to this collisional orogeny, we herein name this event the Klondike orogeny.

4.2. Tectonic Setting of Triassic Sedimentation

4.2.1. Early to Middle Triassic Strata Along the North American Margin—Evidence for the Klondike Foreland Basin

[43] The detrital zircon ages of Triassic marine strata deposited along the ancestral North American continental margin offer key data into the tectonic development of northwestern Canada. The five sandstone samples (499 U-Pb zircon analyses) collected from various late Ladinian to Norian successions exhibit strong provenance ties to local source rocks exposed on either side of the Inconnu thrust (and its equivalents) in the northern Canadian Cordillera. For example, Early Mississippian to Late Permian (357–252 Ma) detrital zircon ages observed in all five samples overlap with the U-Pb zircon crystallization ages of magmatic rocks that characterize Paleozoic arc assemblages of the Yukon-Tanana terrane [*Nelson et al.*, 2006]. The more prevalent 360–700 and 1000–2000 Ma detrital zircon populations in each of these samples are most similar to those that distinguish Mississippian to Triassic siliciclastic strata of the ancestral North American continental margin in Yukon, including previously analyzed Triassic rocks in eastern Yukon (Figure 8f) [*Beranek et al.*, 2010a]. The relatively minimal amount of detrital zircon ages that cluster at ca. 1870, 2080, 2380, and 2720 Ma suggest the Snowcap assemblage was not a major source for the Triassic strata.

[44] The presence of mid- to late Paleozoic detrital zircon in Triassic continental margin rocks requires that the Yukon-Tanana terrane was in proximity to, or had overridden, the Laurentian margin of northwestern Canada by Olenekian to late Ladinian time, and by extension, that the Slide Mountain ocean was narrow or had already closed. The magmatic and tectonic history of the Klondike District defined by this study is most consistent with Late Permian arc-continent collision being the impetus for mid- to late Paleozoic detrital zircon within Triassic continental margin strata. We infer therefore that arc-continent collisional processes related to the Klondike orogeny accommodated tectonic loading and foreland-style basin formation along the ancestral North American continent margin. Basin filling of the Klondike foreland likely ceased by the Carnian, during the deposition of regional overlap assemblages (see later discussion).

[45] Although the amount of zircon from the Yukon-Tanana terrane arc infrastructure is generally small (~15%) relative to the recycled continental margin components (~85%), the new results from Early to Middle Triassic strata of Yukon are consistent with the provenance signatures of foreland basin strata adjacent to other ancient arc-continent collisional systems [e.g., *Clift et al.*, 2009; *Park et al.*, 2010]. The relatively minor amount of Yukon-Tanana arc-derived zircon in the Triassic sedimentary record may indicate that: (1) North American continental margin strata are more fertile in zircon than magmatic rocks of the northern Cordilleran terranes, creating a natural bias; (2) collision of the Klondike arc with western North America generated a thrust stack of imbricated continental margin rocks that were a dominant source region; (3) topographic relief of the accreted Klondike arc in Early to Middle Triassic time was relatively subdued; and/or (4) Klondike foreland strata rich in arc-derived zircon are now structurally buried post-Triassic allochthons, as Jurassic and Cretaceous motion of the Inconnu thrust and equivalents have affected much of the study area, overprinting and obscuring original stratigraphic and structural relationships.

4.2.2. Late Triassic Strata—Evidence for a Regional Overlap Assemblage

[46] The wide geographic extent and large sample suite of Triassic clastic strata that overlie the Slide Mountain terrane record many aspects of regional tectonics and sedimentation in the northern Cordillera which were previously only inferred from bedrock mapping studies. The ten samples (724 U-Pb zircon analyses) of Carnian to Rhaetian sandstone collected along a strike length of ~800 km from eastern Alaska (American Creek area) through central Yukon (Tummel fault zone) to northern British Columbia (Sylvester allochthon) contain generally indistinguishable detrital zircon age patterns. The repeatable detrital zircon signatures are interpreted to indicate a well-mixed Late Triassic depositional system. Because these Carnian to Rhaetian strata yield 360–700 and 1000–2000 Ma detrital zircon age populations similar to Triassic rocks underlain by the ancestral North American margin (Figure 8), although in different proportions, we conclude that Late Triassic strata in the northern Cordillera formed a sedimentary overlap assemblage which covered the Slide Mountain terrane, Yukon-Tanana terrane, and western North America. These data strengthen the argument for the timing of Late Permian arc-continent collision and source for Early to Middle Triassic strata in the northern Cordillera. Overlap assemblage strata to the west of Inconnu thrust are probably no younger than Carnian in age, which suggests that accretion-related subsidence in the Klondike foreland was over by that time.

[47] Five samples (336 U-Pb zircon analyses) of coarse-grained Triassic strata that occur with deformed Slide Mountain assemblage rocks in the northern Finlayson Lake

belt and McNeil Lake klippe are characterized by unimodal, 250–270 Ma detrital zircon age profiles suggestive of first-cycle sediment. The available data are most consistent with the Triassic strata being primarily sourced from exhumed Permian magmatic rocks of the Klondike arc or its forearc basin, with little to no sedimentary input from western North America. Ubiquitous chert rock fragments in northern Finlayson Lake belt strata are probably derived from the underlying Slide Mountain assemblage.

[48] Middle to Late Triassic (245–213 Ma) detrital zircons that occur in most Late Triassic samples in our study have uncertain provenance and tectonic significance. Regardless of host lithology or sample location, the ages of these zircons appear to focus around 242, 236, and 222 Ma. Voluminous felsic magmatism within the Yukon-Tanana terrane after the Klondike orogeny is not recognized prior to ~212 Ma [*Mortensen*, 1992]; however, the oldest felsic rocks of Mesozoic Quesnellia and Stikinia in the northern Cordillera are Middle Triassic in age. For example, 236–215 Ma felsic plutonic, volcanic, and volcaniclastic rocks occur within Mesozoic Stikinia in the Iskut River area of northern British Columbia [*Anderson*, 1993]. Northeast of the Tintina fault, further hints of local Triassic magmatic activity are recorded by 232–226 Ma gabbro and diorite sills that intrude Paleozoic continental margin strata in western Yukon and eastern Alaska [*Mortensen and Thompson*, 1990; *Dashevsky et al.*, 2003; *Dusel-Bacon et al.*, 2006]. Occurrences of Triassic detrital zircons in overlap assemblage strata from eastern Alaska to the Sylvester allochthon may be most consistent with a source from an emerging continental arc (see later discussion on Triassic-Jurassic magmatism).

4.3. Implications for the Size and Evolution of the Slide Mountain Ocean

[49] The presence of Permian macrofossils of McCloud belt affinity at several localities on the Slide Mountain and Yukon-Tanana terranes (see summary by *Nelson et al.*, 2006), together with paleomagnetic results suggesting ~2000 km of northward displacement of Pennsylvanian-Permian rocks of the Slide Mountain assemblage in the Sylvester allochthon [*Richards et al.*, 1993], has led some workers to speculate that the Slide Mountain ocean must have been several thousand kilometers wide [e.g., *Stevens et al.*, 1990; *Nelson et al.*, 2006, 2009]. Our dating results help constrain the possible size and tectonic evolution of the Slide Mountain ocean basin. Arc magmatism related to the west-dipping subduction of the Slide Mountain ocean is no younger than 254 Ma in southeastern Yukon [*Murphy et al.*, 2006], and subduction had ceased and the Yukon-Tanana terrane had collided with and overridden the Laurentian margin by 252.5 Ma in western Yukon (this study). The timing of initiation of subduction along the southwestern margin of the Slide Mountain ocean is somewhat more difficult to constrain. The oldest dated rock unit interpreted to have been generated during subduction of the Slide Mountain ocean in western Yukon is 262.4 ± 2.2 Ma [*Mortensen*, 1990]. However, blueschist and eclogite interpreted to have formed within the associated subduction zone in central and southeastern Yukon give U-Pb and $^{40}Ar/^{39}Ar$ ages of 240 to 274 Ma, with the oldest ages clustering around 269 Ma [*Erdmer et al.*, 1998; *Fallas et al.*, 1998]. In addition, intrusive rocks of the Yukon-Tanana terrane in southern Yukon and the Sylvester allochthon in northern British Columbia have calc-alkaline compositions consistent with a subduction-related setting [*Piercey et al.*, 2006] and give U-Pb zircon ages of 258–270 Ma (see summary by *Nelson et al.* [2006]). Thus the maximum duration of subduction-related magmatism associated with closure of the Slide Mountain ocean is approximately 24 m.y. (274 to 252 Ma, and allowing for 2 m.y. to achieve blueschist/eclogite facies metamorphic conditions within the subduction zone). The maximum possible convergence rates during closure of the Slide Mountain ocean would be 15–20 cm/yr, which would correspond to a width of 3600–4800 km. A more realistic estimate of 5–10 cm/yr for the convergence rate would correspond to a width of 1200–2400 km. Because the convergent margin was oriented roughly northwest-southeast during the Permian, northward displacement of the Yukon-Tanana terrane during closure of the Slide Mountain ocean would have been substantially less than the actual width of the ocean. This amount of displacement is inconsistent with the much greater northward displacement implied by McCloud belt fauna and the paleomagnetic results reported for the Sylvester allochthon by *Richards et al.* [1993].

[50] Dextral strike-slip faulting in the Slide Mountain ocean is one potential mechanism to explain the discrepancy between the northward displacement of > 2000 km seemingly required by faunal associations and paleomagnetic studies and the < 2000 km of northward displacement that can be accommodated by simple subduction. The Jules Creek fault in the Finlayson Lake belt of southeastern Yukon (JCF in Figure 3) is a strike-slip fault that separates rock units of the Yukon-Tanana terrane on the southwest and Slide Mountain terrane on the northeast, and is inferred to have accommodated significant dextral displacement prior to ~274 Ma [*Murphy et al.*, 2006]. Displacement on the Jules Creek fault appears to pre-date closure of the Slide Mountain ocean, but could still have accommodated sufficient northward displacement of the Yukon-Tanana and Slide Mountain terranes prior to the initiation of subduction to explain the paleomagnetic and faunal evidence, all of which comes from pre-274 Ma rock units. The Blue Dome fault (BDF in Figure 3), a steep structure that runs along the length of the Sylvester allochthon, is a fossil intraoceanic transform fault that could have accommodated motion similar to the Jules Creek fault in Permian time [*Nelson and Bradford*, 1993; *Nelson and Friedman*, 2004; *Nelson et al.*, 2006].

4.4. Late Permian-Early Triassic Convergent Margin Processes Along Western North America

[51] The timing and provenance record of the Klondike orogeny as documented in this article contributes valuable new information into the age and synchroneity of Late Permian-Early Triassic convergent margin processes along western North America. Herein, we present a modified tectonic model for the North American Cordillera (Figure 12) and briefly discuss some of the relevant geological relationships in four areas: Yukon, British Columbia, the Great Basin of central Nevada, and Mojave Desert of southeastern California. The paleogeographic base map and pericratonic terrane associations for our tectonic model are adapted from work by *Nelson et al.* [2006].

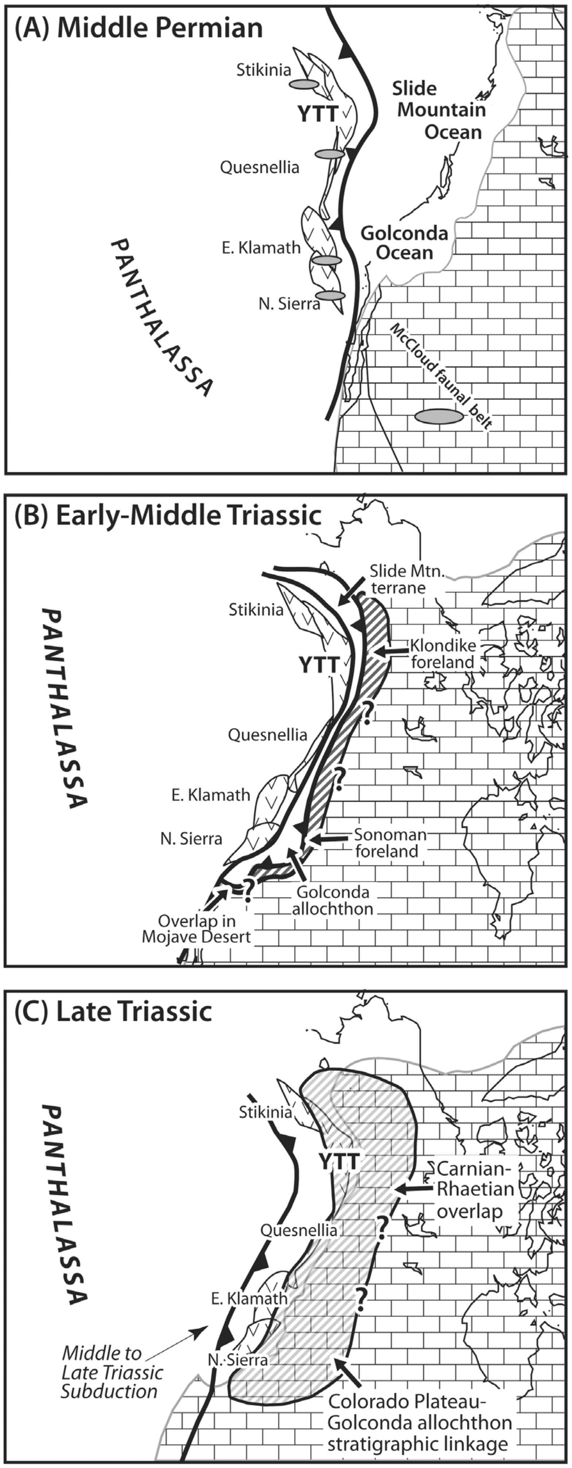

Figure 12. (a) Middle Permian, (b) Early to Middle Triassic, and (c) Late Triassic paleogeographic reconstructions that highlight the tectonic, magmatic, and sedimentary evolution of western North America. Gray discs in Middle Permian reconstruction indicate the location of Permian macrofossils of McCloud belt affinity. Abbreviation: YTT – Yukon-Tanana terrane. Modified from *Nelson et al.* [2006].

4.4.1. Yukon, Canada

[52] The most complete geological record of magmatism, metamorphism, and sedimentation related to Permian and Triassic plate convergence and arc-continent collision along the length of the Cordilleran orogen is observed in Yukon. A southwest to northeast transect across Yukon preserves all of the geological components required to define arc-continent collision: (1) a deformed and metamorphosed magmatic arc terrane; (2) a belt of eclogite and blueschist facies rocks; (3) the remnants of a closed ocean basin; and (4) a foreland-like basin along the continental margin.

[53] The tectonic style of the Klondike orogeny in the Klondike District is fundamentally recorded by the D1 and D2 recrystallization fabrics associated with Late Permian (260–252.5 Ma) ductile deformation, and more regionally in western Yukon, by middle greenschist to upper amphibolite facies dynamothermal metamorphism [e.g., *Villeneuve et al.*, 2003]. Crustal shortening related to arc-continent collision was probably accommodated at structurally deep levels within the Klondike arc, but at structurally high levels in tectonic slices of the Slide Mountain terrane that were imbricated and thrust toward the continent. The lack of a tectonic fabric in the Jim Creek pluton suggests that shortening within the relatively deep portions of the Klondike arc in the Klondike District ceased by latest Permian time. The development of sub-Triassic unconformities on the Yukon-Tanana terrane, Slide Mountain terrane, and ancestral North American margin in Yukon was most likely a response to arc-continent collision.

[54] In our tectonic reconstruction, we suggest that flare-up of the Klondike arc occurred ~1500–2000 km south and west of its current position (YTT in Figure 12a). Closure of the Slide Mountain ocean resulted in Late Permian arc-continent collision and development of a Triassic foreland-style basin on the ancestral North American margin to the east of the Yukon-Tanana terrane (Figure 12b). Deposition of the Late Triassic overlap assemblage was probably coeval with subduction-related magmatism in the northern Cordillera (Figure 12c) that blossomed from Late Triassic to Early Jurassic (212–185 Ma) time [*Mortensen*, 1992].

4.4.2. British Columbia, Canada

[55] A series of geological field relationships in British Columbia have been used as an indirect means to determine the timing of late Paleozoic-early Mesozoic plate convergence in the southern Canadian Cordillera. *Read and Okulitch* [1977] reviewed the evidence for a regionally extensive sub-Triassic angular unconformity on Quesnellia in south-central British Columbia. Beneath the unconformity, they reported that Paleozoic rocks of Quesnellia were deformed by at least two phases of folding and metamorphosed to greenschist facies, whereas Late Triassic strata above the unconformity lack this tectonism. Bedrock mapping studies conducted east of Quesnellia in south-central British Columbia have interpreted that oceanic rocks of the Slide Mountain assemblage were imbricated in typical thrust belt style and emplaced eastward over the North American continental margin in Late Permian-Early Triassic time [*Klepacki*, 1985; *Schiarizza*, 1989]. Detailed structural mapping in the Sylvester allochthon led *Harms* [1986] to also suggest that Late Permian-Early Triassic thrusting affected Slide Mountain assemblage rocks in northern British Columbia. More recently, whole-rock geochemical and Nd

isotope studies demonstrated that Late Triassic strata of Mesozoic Quesnellia arc were depositionally linked with western North America [*Unterschutz et al.*, 2002].

[56] Our tectonic reconstructions suggest that closure of the Slide Mountain ocean brought Quesnellia in proximity to western North America (Figures 12a and 12b). Although it appears that high structural levels of the Quesnellia arc were affected by pre-Late Triassic deformation and metamorphism, the timing and nature of tectonism is poorly constrained. No detrital zircon or stratigraphic studies of Triassic strata have yet investigated a possible foreland record of Permian-Triassic Quesnellia tectonism. However, the Late Triassic overlap assemblage documented by *Unterschutz et al.* [2002] is consistent with our model for the northern Cordillera (Figure 12c).

4.4.3. Great Basin, Nevada, United States

[57] The Great Basin of the western United States is traditionally considered to be the "homeland" for Late Permian-Early Triassic tectonics in the Cordilleran orogen, although there is still no consensus on the exact nature and geometry of convergent margin processes that generated the Sonoman orogeny. Much of the debate has focused on the emplacement of deep-water clastic and mafic volcanic rocks of the Golconda allochthon eastward above the Golconda thrust onto upper slope facies strata of the ancestral North American margin. Emplacement of the Golconda allochthon is generally thought to have resulted from either: (1) arc-continent collision related to westward subduction of Golconda ocean lithosphere beneath east-facing arc terranes [*Speed*, 1979]; or (2) noncollisional collapse of the Golconda ocean basin due to changes in plate motions within a west-facing subduction system [e.g., *Burchfiel and Davis*, 1975]. Sub-Triassic angular unconformities observed on arc terranes to the west of the Golconda allochthon are interpreted to reflect widespread uplift, along with local folding and faulting, during Late Permian to Early Triassic time [*Wyld*, 1991].

[58] In central Nevada, felsic volcanic rocks of the Early Triassic Koipato Group unconformably overlie deformed units of the Golconda allochthon. High-precision U-Pb zircon geochronology has recently pinned the age of the Koipato Group between 250 and 248 Ma [*Vetz et al.*, 2010], suggesting pre-Triassic emplacement of the Golconda allochthon. Continental margin rocks near the eastern California-western Nevada border are overlain by ~1000 m-thick succession of Olenekian volcaniclastic strata of the Candelaria Formation, which are in turn tectonically overlain by fault slices of serpentinite and the Golconda allochthon. Arc volcanics that are presently west of the Golconda allochthon may be the source of the volcaniclastic strata [*Speed*, 1984], suggesting that arc-continent collision commenced by the Early Triassic.

[59] Based on the available data, we suggest that emplacement of the Golconda allochthon was a result of convergent margin processes surrounding Late Permian arc-continent collision (Figures 12a and 12b). The absence of blueschist or eclogite belts paired with Permian arc assemblages in Great Basin hinders an attempt to decipher an arc-continent collisional model. This absence implies that high temperatures under North America extended far west from its margins to prevent low thermal gradients under accreting terranes [*Rogers and Bernosky*, 2008]. The development of foreland-like basins to the east of the Golconda allochthon during the Triassic has not yet been proven but is permissive [*Dickinson*, 2006] and testable by future provenance studies. Late Triassic overlap assemblages from the Golconda allochthon eastward to the Colorado Plateau developed in the backarc region (Figure 12c) to a Late Triassic continental arc system [*Riggs et al.*, 1996; *Manuszak et al.*, 2000].

4.4.4. Mojave Desert, California, United States

[60] A complex history of convergent margin processes affected the ancestral North American continental margin in the Mojave Desert region (Figure 1), south of the Great Basin of Nevada. In this region, the change from a passive margin to convergent margin setting in late Paleozoic to early Mesozoic time was apparently related to sinistral transform faulting and truncation of stratigraphic and structural trends [e.g., *Walker*, 1988; *Saleeby and Busby-Spera*, 1992].

[61] U-Pb zircon geochronological studies in the northern Mojave Desert have shown that intrusion of Late Permian (260 ± 5 Ma) quartz monzonite into the local eugeoclinal succession was synkinematic with west-southwest-directed folding and thrust faulting, whereas an undeformed biotite-hornblende granodiorite to tonalite with an age of 246 ± 3 Ma suggests that deformation ceased by Early to Middle Triassic time [*Miller et al.*, 1995]. In the Victorville area, Paleozoic metasedimentary rocks isoclinally folded and metamorphosed to upper greenschist facies were intruded by a post-tectonic monzonite pluton dated by U-Pb zircon at 241 Ma [*Miller*, 1981; *Walker*, 1988]. In the western Mojave Desert, Cordilleran arc magmatism began by the earliest Triassic (250 Ma), and progressively swept eastward and southwards during late Ladinian (235–231 Ma) time [*Barth and Wooden*, 2006].

[62] Olenekian siliciclastic strata of the Mojave Desert that are time-correlative with the Candelaria Formation in the Great Basin comprise an overlap assemblage deposited over deformed and metamorphosed rocks. *Walker* [1988] used this stratigraphic relationship as evidence for plate convergence in the Mojave Desert region to broadly pre-date that associated with the Sonoman orogeny in Nevada, although the new U-Pb zircon studies of the Koipato Group [*Vetz et al.*, 2010] imply rocks of the Golconda allochthon were deformed prior to the earliest Triassic (250–248 Ma).

[63] We infer the Slide Mountain-Golconda ocean during the Middle Permian narrowed toward to the south (Figure 12a), providing a plate margin boundary along the southwestern United States that accounts for the complex interplay of subduction, deformation, and metamorphism observed in the Mojave Desert. During the Early and Middle Triassic, undeformed plutons and sedimentary overlap assemblages apparently provide an upper limit for the age of continental margin deformation (Figure 12b). Triassic arc magmatism of the region spans from at least 250–210 Ma, coeval in part with 232–210 Ma plutons in the Sierra Nevada batholith of Nevada [*Saleeby and Busby-Spera*, 1992; *Barth and Wooden*, 2006].

4.5. Implications for Triassic-Jurassic Arc Magmatism in Western North America

[64] Volcanic assemblages and associated plutons of Middle Triassic to Early Jurassic age are observed within pericratonic terranes along the entire length of the Cordilleran

orogen from Yukon to California [e.g., *Dickinson*, 2004; *Nelson and Colpron*, 2007]. Based on the results of our study, we suggest that Middle Triassic to Early Jurassic magmatism is related to a continuous, west-facing continental arc system established immediately following Late Permian-Early Triassic arc-continent collision and orogenesis in western North America (Figure 12c). The timing and pattern of subduction initiation along the western margin of the accreted terranes is unclear; however, flips in subduction polarity are an anticipated consequence of arc-continent collision [e.g., *Cooper and Taylor*, 1987; *Lister et al.*, 2001]. Nonetheless, Late Permian-Early Triassic orogenesis apparently played a key role in generating east-dipping subduction beneath western North America during the early Mesozoic, and by extension, the birth of accretionary tectonism that characterizes the Cordilleran orogen.

4.6. Are Early Cordilleran Orogenesis and Arc Magmatism Linked to Supercontinent Assembly?

[65] The apparent synchroneity of Late Permian-Early Triassic collisional orogenesis and Middle Triassic to Early Jurassic arc magmatism along the length of western North America provides a stunning example of how major (>1000s of kilometers long) plate boundaries accommodate and evolve with continent-scale plate convergence. However, a first-order problem in Cordilleran tectonics still remains: why did the Slide Mountain ocean start to close in the Early to Middle Permian?

[66] On a global scale, the Permian and Triassic periods of interest to this study occurred during the final assembly of Pangaea, the last supercontinent to have existed on Earth. Pangaea was an amalgam of the paleocontinents Gondwana, Laurussia (Laurentia and Baltica), and Siberia-Kazakhstan-Asia. These continental blocks were sequentially sutured together in several collisional orogens, including the Late Carboniferous to Early Permian phase of the Uralian orogen that juxtaposed present-day Siberia with eastern Europe. Although speculative, we suggest that the timing of late Paleozoic Uralian collision may be of particular relevance in Cordilleran tectonics. For example, some global plate reconstructions depict the Uralian and Cordilleran systems as being connected by a singular subduction plate margin or strike-slip plate margin during Pennsylvanian to Permian time [*Ziegler*, 1989; *Nelson and Colpron*, 2007]. The proposed late Paleozoic plate margin would have extended from the Cordilleran pericratonic realm northward and eastward around present-day Arctic Canada and the Barents Shelf to the Uralian margin. Late Carboniferous to Early Permian Uralian orogenesis is viewed as a suitable mechanism in which to cause global plate reorganization, possibly affecting the subduction polarity and plate motions associated with the Cordilleran pericratonic terranes and Slide Mountain ocean. The synchroneity of continent-scale plate convergence along western North America during the Late Permian-Early Triassic implies that the driving force for marginal ocean closure reflects a significant plate tectonic event. As an analogue, *Cawood and Buchan* [2007] recently proposed that global plate kinematic adjustments during collisional orogenesis and assembly of Pangaea directly led to subduction initiation, terrane accretion, and contractional orogenesis within late Paleozoic-early Mesozoic accretionary orogens along the Pacific margin of Gondwana. Tectonic processes exterior to western North America may therefore have put in motion a series of events that profoundly affected early tectonic development of the Cordillera.

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