Provenance of North American Triassic strata from west-central and southeastern Yukon: correlations with coeval strata in the Western Canada Sedimentary Basin and Canadian Arctic Islands

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Abstract: New detrital mineral age and whole-rock geochemical data provide the first constraints on the composition and source of North American Triassic strata in the northern Canadian Cordillera. Conodont-bearing Triassic strata collected from five locations across west-central to southeastern Yukon contain trace-element ratios ($(La/Yb)_N = \sim 8$; $Eu/Eu^* = \sim 0.66$), $\varepsilon Nd_{(248\ Ma)}$ values (–9 to –10), and detrital zircon ages (400–680, 980–1200, 1500–1650, 1800–2000 Ma) that correspond with those of coeval rocks in the Canadian Arctic Islands and the Western Canada Sedimentary Basin of British Columbia and Alberta. The majority of detrital zircons were cannibalized from Ellesmerian clastic wedge and western Laurentian margin strata and recycled into Triassic rocks. Conspicuous early Paleozoic and Neoproterozoic detrital zircons may have been ultimately derived from allochthonous rocks of Caledonian–Baltican affinity in northern North America, such as the Pearya and Arctic Alaska – Chukotka terranes. One Early Triassic unit in eastern Yukon contains ca. 360 Ma detrital muscovite, and samples from several localities include single-grain occurrences of Mississippian detrital zircon. Mississippian detrital mineral ages likely record a partial source from mid-Paleozoic rocks of the allochthonous Slide Mountain and Yukon–Tanana terranes following their Late Permian – Early Triassic emplacement onto the Cordilleran margin. More substantial evidence of terrane-derived sediment deposited along the North American margin may be further identified within Triassic strata that are exposed to the west (outboard) of our sample sites, immediately adjacent to the Slide Mountain and Yukon–Tanana terranes.

Résumé : De nouvelles données sur l'âge des minéraux détritiques et la géochimie de la roche entière fournissent le premier cadre pour la composition et la source des strates du Trias d'Amérique du Nord dans la Cordillère canadienne septentrionale. Des strates du Trias contenant des conodontes ont été recueillies à cinq endroits du centre-ouest au sud-est du Yukon; elles contiennent des rapports d'éléments traces ($(La/Yb)_N = \sim 8$; $Eu/Eu^* = \sim 0{,}66$), des valeurs de $\varepsilon Nd_{(248\ Ma)}$ de –9 à –10, et des âges de zircons détritiques (400–680, 980–1200, 1500–1650, 1800–2000 Ma) qui correspondent à ceux de roches de même âge dans les îles de l'Arctique canadien et du bassin sédimentaire de l'Ouest canadien en Colombie-Britannique et en Alberta. La plupart des zircons détritiques ont été cannibalisés de strates du coin de sédiments clastiques ellesmériens et de strates de la bordure laurentienne puis recyclés dans des roches du Trias. Des zircons détritiques proéminents du Paléozoïque précoce et du Néoprotérozoïque pourraient à la limite provenir de roches allochtones d'affinité calédonienne-balte dans le nord de l'Amérique du Nord, telles que les terranes de Pearya et d'Alaska – Chukotka dans l'Arctique. Une unité du Trias précoce dans l'est du Yukon contient de la muscovite détritique datant d'environ 360 Ma et des échantillons de plusieurs localités comprennent des occurrences de grains uniques de zircon détritiques datant du Mississippien. Les âges des minéraux détritiques datant du Mississippien enregistrent probablement une source partielle de roches du Paléozoïque moyen des terranes allochtones de Slide Mountain et de Yukon–Tanana à la suite de leur mise en place au Permien tardif – Trias précoce dans la bordure de la Cordillère. Des évidences plus substantielles de sédiments dérivés de terranes et déposés le long de la bordure nord-américaine peuvent être mieux identifiées dans les strates du Trias qui affleurent à l'ouest (à l'extérieur) de nos sites d'échantillonnage, immédiatement adjacentes aux terranes de Slide Mountain et de Yukon–Tanana.

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Introduction

Triassic strata of the eastern Canadian Cordillera and adjacent autochthon are recognized as a variable sequence of continental margin rocks exposed from the Canadian Arctic Islands south to the United States border (Gibson 1993). Detailed stratigraphic and compositional studies of the North American Triassic sedimentary record focused primarily on the Western Canada Sedimentary Basin (WCSB; Fig. 1) of British Columbia and Alberta, where these strata host >975 million barrels (1 barrel oil US gallons = 0.159 m^3) of conventional oil and 10 trillion cubic feet (1 ft^3 = 28.317 dm^3) of marketable gas (Davies 1997; Ross et al. 1997).

North American Triassic rocks north of the WCSB principally comprise muscovite-bearing siltstone and sandstone, shale, and limestone exposed in discontinuous belts from west-central to southeastern Yukon, mainly northeast of the Tintina fault (Fig. 1). Scientific literature reviews of early Mesozoic sedimentation in western Canada note the occurrence of North American Triassic strata in Yukon, but the paucity of information on these units at the time of publication generally resulted in their exclusion from continent-scale models on Cordilleran margin evolution (Gibson 1993; Davies 1997). The source and paleotectonic setting of North American Triassic siliciclastic rocks in Yukon has, therefore, remained enigmatic to the Cordilleran geoscience community.

Regional conodont fossil collections and bedrock mapping studies provided constraints on the depositional age and paleoenvironmental setting for numerous occurrences of North American Triassic strata across Yukon (e.g., Orchard 2006); however, the >750 m thick early Olenekian (Early Triassic) Jones Lake Formation type section in eastern Yukon is perhaps the most well-known and best documented example (Fig. 2; Gordey et al. 1981; Gordey and Anderson 1993). Compared with the Jones Lake Formation type section, a minimal amount of geologic information is known about the majority of North American Triassic successions exposed from west-central to southeastern Yukon. As a result, many occurrences of these poorly understood Triassic strata have been assigned to the Jones Lake Formation even if the rock units do not share lithologic or depositional age characteristics with those of the type locality (Fig. 2; e.g., Gordey 2008).

Nelson et al. (2006) considered the easternmost Cordilleran terranes in western Canada to have been emplaced over the western margin of North America in Late Permian – Early Triassic time. The earliest phase of terrane accretion in western Canada was previously suggested to have been ~60 million years later during the Early to Middle Jurassic (e.g., Monger and Price 2002). The Late Permian – Early Triassic tectonic model predicts a regional overlap assemblage covered the accreted terranes and Cordilleran margin of western North America, implying that at least some Triassic rocks across west-central to southeastern Yukon document a western-derived source from mid- to late Paleozoic rocks of the Slide Mountain and Yukon–Tanana terranes (see locations in Fig. 1). Provenance analysis of North American Triassic strata required to test this model is presumed to be relatively simple because detrital zircon and detrital muscovite derived from Slide Mountain and Yukon–Tanana terrane rocks (western source) should yield mineral ages that are distinguishable from those of a Laurentian-only origin (eastern source).

In this paper, we present new detrital mineral age and whole-rock geochemical data from Triassic strata across west-central to southeastern Yukon. Five Triassic stratigraphic successions distributed over a wide geographic area, including that of the Jones Lake Formation type section, were selected for provenance analysis on the basis of their conodont fossil age control and demonstrable ties to the North American continental margin sequence. New conodont fossil data for the Jones Lake Formation type section are also presented. The source and composition of Permian strata underlying the Jones Lake Formation was investigated at two localities.

The primary objectives of our study were to (1) construct the first detrital mineral age and geochemical reference frame for Triassic rocks in Yukon to allow for direct comparisons with coeval strata in the WCSB and the Canadian Arctic Islands; and (2) evaluate the Late Permian – Early Triassic emplacement of the easternmost Cordilleran terranes onto the North American margin (e.g., Nelson et al. 2006) by testing for the presence of western-derived, mid- to late Paleozoic detrital mineral components and whole-rock geochemical signatures that are not consistent with a Laurentian-only source.

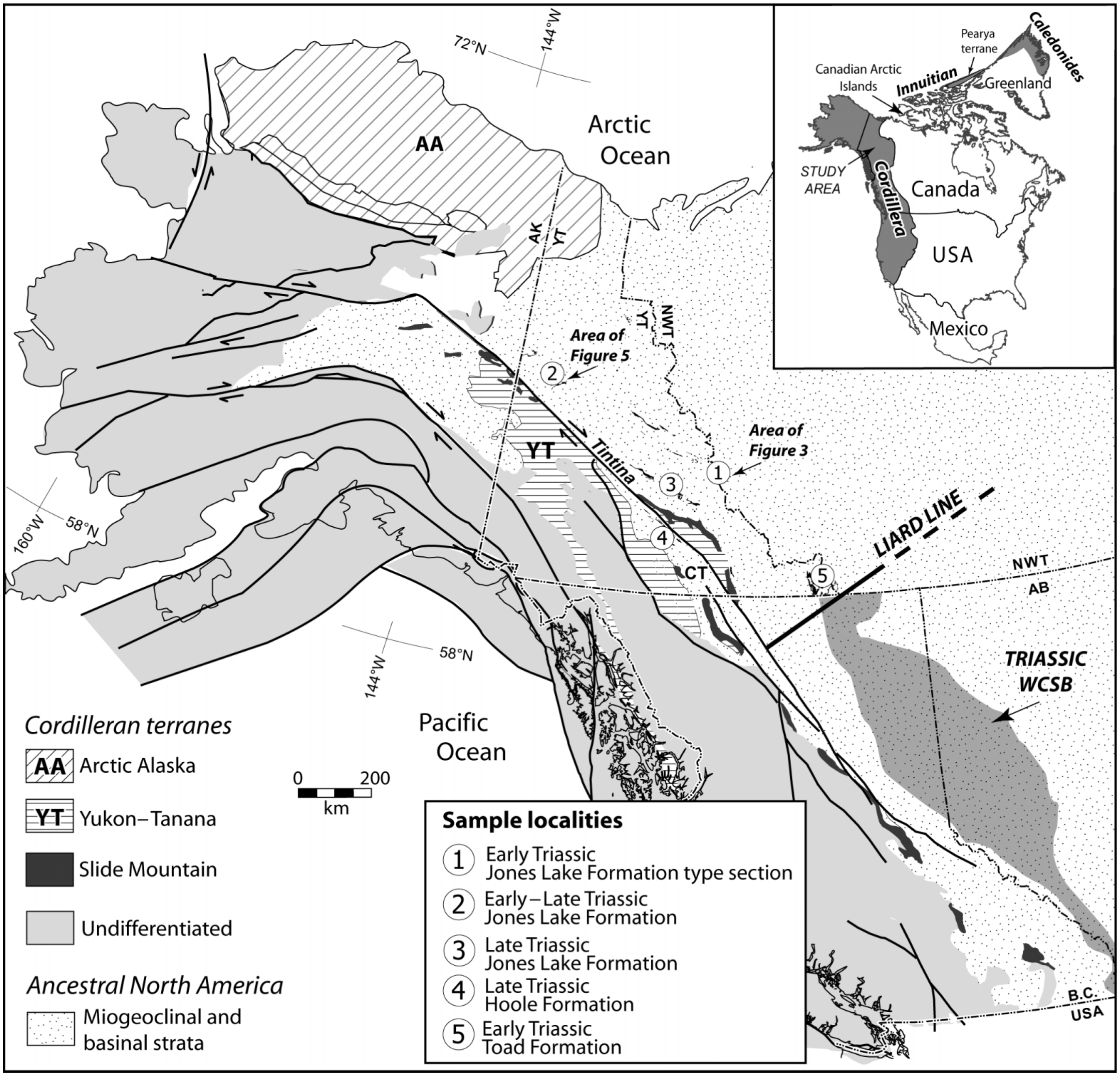
Geologic setting of Triassic strata in western Canada

Field, drillhole, and geophysical studies generated robust geologic constraints on Triassic strata of the WCSB in British Columbia and Alberta (e.g., Gibson and Barclay 1989; Davies 1997). These workers concluded that Triassic strata in the southern Canadian Cordillera were deposited in a west-facing, mid-latitudinal, passive margin environment along the western edge of the Pangean supercontinent. Davies (1997) divided the WCSB into four basins or subbasins during the Triassic, encompassing a range of extensional, transtensional, and continental sag depocentres.

In contrast, regional studies in northern British Columbia and Yukon recognized that Late Devonian to Triassic rocks in the northern Canadian Cordillera were deposited along the eastern side of a marginal ocean basin, informally named the Slide Mountain – Golconda ocean (e.g., Nelson 1993; Piercey et al. 2004; Colpron et al. 2007). This ocean developed as a back-arc basin alongside western North America from mid- to late Paleozoic time coincident with magmatic activity on the adjacent Yukon–Tanana terrane and related pericratonic elements (Nelson et al. 2006). The earliest phases of Slide Mountain – Golconda ocean closure began by the Middle Permian (Mortensen 1992), facilitating eastward transport and eventual emplacement of Yukon–Tanana and related terranes onto the North American continental margin during the Late Permian – Early Triassic (Nelson et al. 2006). Vestiges of the Slide Mountain – Golconda ocean in the northern Cordillera form the Slide Mountain terrane (Nelson 1993).

Mississippian to Triassic strata in west-central to southeastern Yukon were deposited within a clastic shelf system developed over early to mid-Paleozoic basinal and turbidite

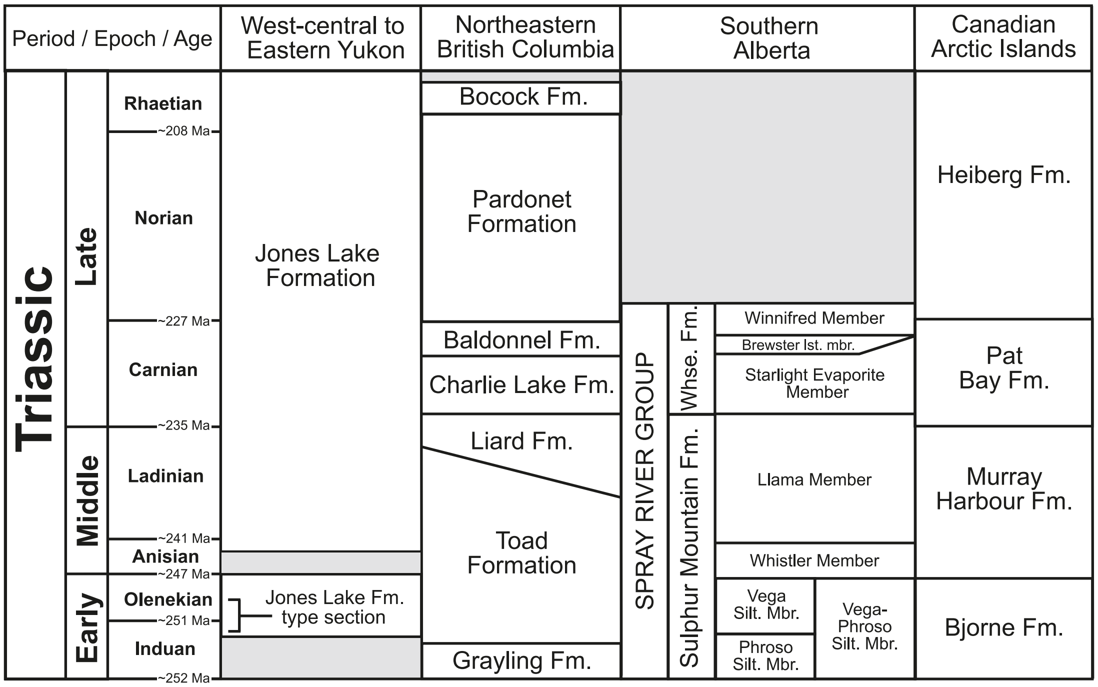
Fig. 1. Generalized tectonic element map of the Canadian and Alaska Cordillera. Sample localities 1–5 discussed in the text are shown by numbered white circles. North American Triassic strata that crop out in Yukon are shown by northwest-trending, thin black polygons within ancestral North America map unit. Surface and subsurface extent of Triassic strata in the Western Canada Sedimentary Basin (WCSB) depicted by shaded grey area within ancestral North America map unit. Inset map highlights locations of the North American Cordillera, Caledonian and Innuitian orogens, Canadian Arctic Islands, and Pearya terrane. Map modified from Colpron et al. (2006) and Colpron and Nelson (2009) with data adapted from Cecile et al. (1997), Davies (1997), and Gordey and Makepeace (2001). AB, Alberta; AK, Alaska; B.C., British Columbia; CT, Cassiar terrane; NWT, Northwest Territories; USA, United States of America.



assemblages of the Selwyn and Earn basins, respectively (Gordey et al. 1991; Gordey and Anderson 1993). Triassic rocks in southeastern Yukon are also assigned to the Cassiar terrane, a displaced fragment of the Cordilleran passive margin sequence presently located southwest of the Tintina fault (CT in Fig. 1; Gordey 1981). Paleozoic and Triassic strata of Cassiar terrane were deposited in a restricted platformal setting outboard of North American assemblages (Gordey 1981; Gordey and Anderson 1993).

The boundary area between North American Triassic units in southeastern Yukon and those in the northern WCSB of British Columbia and Alberta roughly corresponds with a northeast-trending structural zone named the Liard Line (Fig. 1). Cecile et al. (1997) concluded the Liard Line represents a structural transfer zone, which separates a lower-plate margin to the north (Yukon) and upper-plate margin to the south (Alberta and British Columbia). Asymmetric rifting of the supercontinent Rodinia established the differ-

Fig. 2. Generalized stratigraphy of North American Triassic rocks in Yukon, northeastern British Columbia, southern Alberta, and Canadian Arctic Islands. Triassic time scale from Brack et al. (2005), Lehrmann et al. (2006), Ovtcharova et al. (2006), Galfetti et al. (2007), Kozur and Bachmann (2008), and Schaltegger et al. (2008). Stratigraphic information modified from Gibson (1993), Davies (1997), and Patchett et al. (2004). Fm., Formation; lst., limestone; mbr., member; Slt., siltstone; Whse., Whitehorse.



ent continental margin settings along western Laurentia (see Lister et al. 1986; Cecile et al. 1997). Dextral strike-slip and transtensional motion along reactivated Liard Line structures affected the thickness and facies distribution of Triassic units in northeastern British Columbia (Davies 1997).

Paleocurrent, sedimentary facies, and isopach data collected from Triassic strata of the WCSB in Alberta and British Columbia define a westward-thickening sedimentary prism with an inferred source from the east-northeast (Gibson and Barclay 1989). Isotopic provenance data indicate Triassic strata of the WCSB are composed of recycled components from rocks of the adjacent Laurentian craton and Ellesmerian clastic wedge of northern Canada (Boghossian et al. 1996; Ross et al. 1997).

Sample localities

Locality 1: Mount Christie and Jones Lake formation stratotypes, eastern Yukon

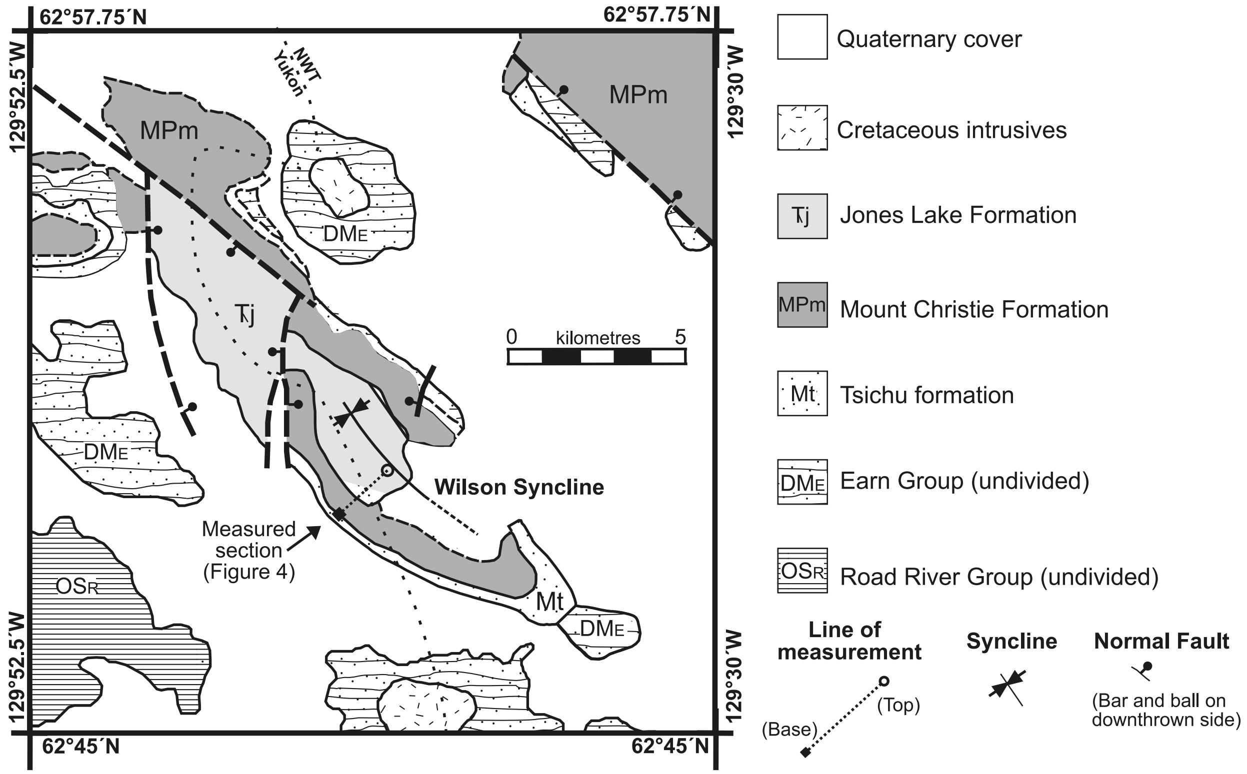
The type sections of the Mississippian–Permian Mount Christie and Triassic Jones Lake formations are exposed in the western limb of the Wilson Syncline in the Little Nahanni River map area (National Topographic System (NTS) 105A) along the eastern Yukon – Northwest Territories border (locality 1 in Fig. 1; Figs. 2, 3). Gordey et al. (1981) and Gordey and Anderson (1993) measured the type sections, reported conodont fossil ages, and formally assigned stratigraphic nomenclature for the section. We remeasured the Mount Christie and Jones Lake formation type sections and collected 14 shale samples for geochemical analysis, two samples each for detrital zircon and muscovite geochronology, and sampled several stratigraphic horizons for conodont fossils (Fig. 4).

The Mount Christie Formation stratotype comprises two informal members (Gordey and Anderson 1993; Fig. 4): a lower shale member (550 m thick) and an upper chert and shale member (200 m thick). The lower member disconformably overlies the Mississippian Tsichu formation (informal; Gordey and Anderson 1993) and is composed of dark grey, green-grey, and red-brown weathering, siliceous shale with minor parallel- to wavy-laminated siltstone. The upper member consists of splintery shale and siltstone intercalated with thin- to medium-bedded, locally nodular, grey and black chert. Barite nodules, up to 0.3 m in diameter, are readily observed above the 400 m level in the section. Fine-grained detrital muscovite occurs along bedding planes throughout the formation. Red weathering limestone containing Early Permian conodonts forms the boundary between the lower and upper members (Gordey and Anderson 1993).

The contact with the Jones Lake Formation stratotype is not exposed at surface. Gordey and Anderson (1993) chose the last occurrence of chert to signify the approximate location of the uppermost Mount Christie Formation. The fine-grain size, general lack of sedimentary structures, and cherty nature of the Mount Christie Formation type section indicate subwavebase deposition in an offshore environment that at times was sediment starved (Gordey and Anderson 1993).

The Jones Lake Formation type section consists of two informal members (Gordey and Anderson 1993; Fig. 4): a lower member (330 m thick) and an upper member (>400 m thick). The lower member contains recessive to moderately resistant, muscovite-bearing, calcareous shale, parallel- to ripple cross-laminated siltstone, and very fine grained sandstone. The upper member is composed of sandy

Fig. 3. Simplified geologic map of the Wilson Syncline region (locality 1) along the eastern Yukon – Northwest Territories (NWT) border. The stratigraphic section of Fig. 4 is indicated by the line of measurement across the western limb of the Wilson Syncline. Geology from Gordey and Anderson (1993).



limestone, resistant, parallel- to ripple cross-laminated siltstone, and fine-grained sandstone with subordinate shale. The upper member forms the core of the Wilson Syncline and has an erosional top. Gordey and Anderson (1993) reported early Olenekian (Smithian) conodonts from a sandy limestone layer 330 m above the formation base. Significant erosion occurred in eastern Yukon during the early Olenekian, as the Jones Lake Formation is underlain by Devonian Earn Group strata in parts of the Little Nahanni River map area (Gordey and Anderson 1993). Orchard (2006) observed reworked Late Mississippian, Early Permian, and Early Triassic (Induan; Griesbachian and Dienerian) conodont fossils in the sandy limestone layer at the base of the upper member.

Jones Lake Formation sandstone contains angular to subrounded, monocrystalline, fine sand-sized quartz and 5%–10% muscovite. Beds have sharp bases and are normally graded. Microhummocky and swaley laminations occur within the lower member. Limited (n = 5) paleocurrent measurements from ripple cross-laminae record east-south-east-directed (margin-parallel) paleoflow. Gordey and Anderson (1993) concluded wave-induced facies in the Jones Lake Formation type section formed in a shallow-marine shelf environment.

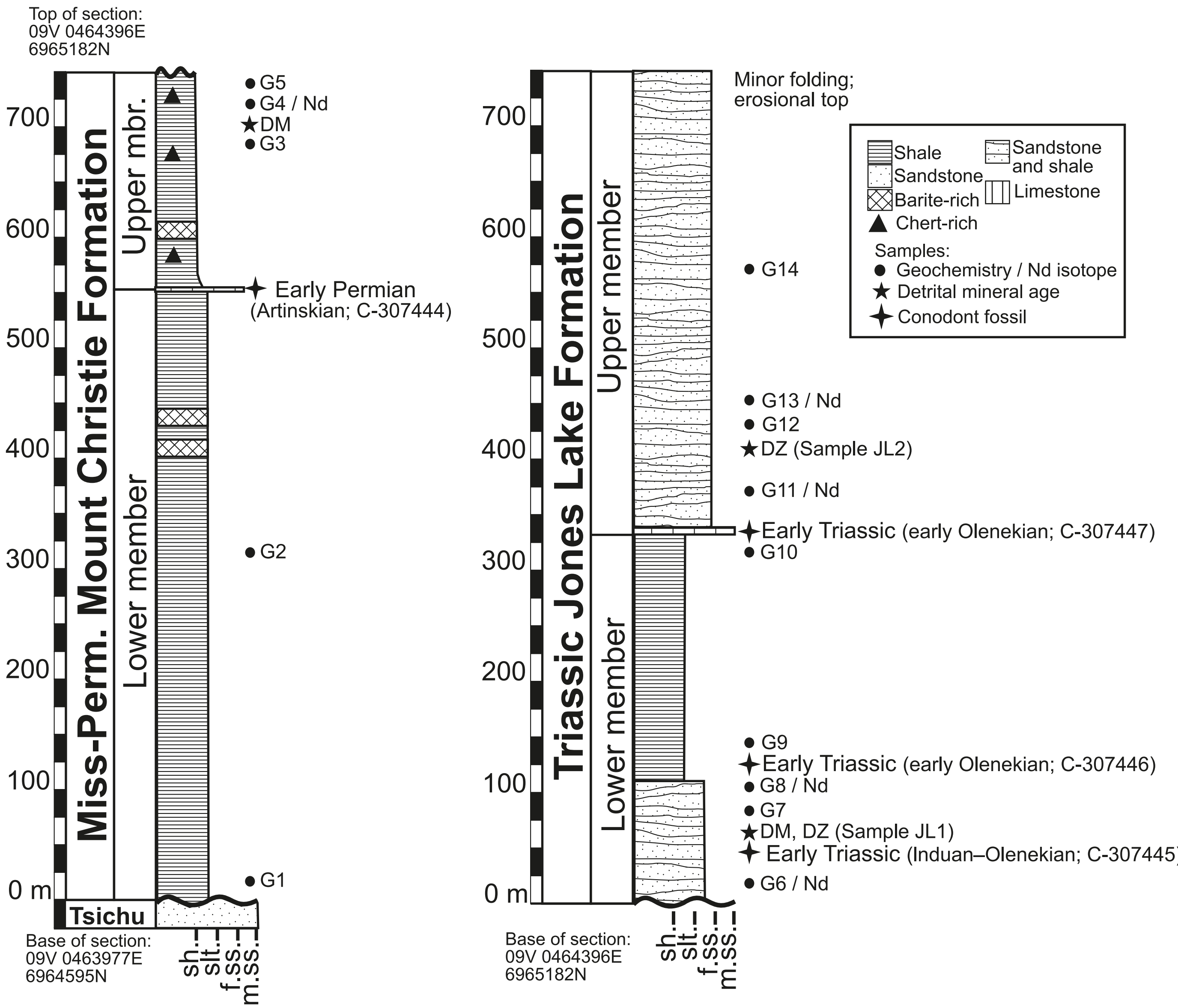
Locality 2: Mount Christie and Jones Lake formations, Ogilvie Mountains, west-central Yukon

Permian and Triassic strata are exposed in the Ogilvie Mountains of west-central Yukon adjacent to Mount Robert Service (locality 2 in Fig. 1; Fig. 5). This area was first mapped and described at a detailed scale by Tempelman-Kluit (1970) and Green (1972). Thompson et al. (1994) produced the most recent 1 : 50 000 geologic map of the region (NTS 116B/8) and referred to Permian and Triassic strata therein as equivalents to the Mount Christie and Jones Lake formations of Gordey and Anderson (1993).

The Mount Christie Formation at locality 2 comprises white, grey-green, and maroon weathering, grey, thinly bedded shale. Tempelman-Kluit (1970) suggested the Mount Christie Formation in this region is ~150 m thick. The contact with the overlying Jones Lake Formation is covered; however, Green (1972) noted, in other portions of the Dawson map area (NTS 116B), Triassic rocks bevel underlying Permian strata and sit in slight angular unconformity above them.

The Jones Lake Formation at locality 2 is tentatively divided into two informal members: a lower member (~300 m thick; unit 15 of Tempelman-Kluit 1970) and an upper member (~100 m thick). The lower member consists of tan to brown weathering, brown to grey, thin to thickly bedded, parallel- to wavy- to ripple cross-laminated, calcareous, muscovite-bearing, shale to fine-grained sandstone. Tempelman-Kluit (1970) reported sandstone from the lower member contains angular quartz grains, sodic plagioclase, and up to 10% detrital muscovite derived from metamorphic source rocks. In general, the lithologic character of the lower member strata is similar to that of the Jones Lake Formation type section. The upper member is composed of recessive shale, siltstone, chert lithic sandstone, feldspathic wacke, and argillaceous to bioclastic to pelecypod-bearing limestone.

Fig. 4. Composite stratigraphic section for the Mount Christie and Jones Lake formation type sections. Conodont fossil ages and Geological Survey of Canada (GSC) curation numbers are from this study (see Fig. 6). Universal Transverse Mercator locations are in North American datum 1983 (NAD 83). See text for sample information and supplementary data Tables S1–S4[4] for geochemical and isotopic results. DM, detrital muscovite; DZ, detrital zircon; f.ss, fine sandstone; mbr., member; Miss–Perm., Mississippian–Permian; m.ss, medium-grained sandstone; Nd, neodymium; sh., shale; slt., siltstone.



Tempelman-Kluit (1970) and Orchard (2006) reported Early to Late Triassic (early Olenekian to Norian) macro- and microfossil collections in the Mount Robert Service area. We tentatively assign the lower and upper members to be Early to Middle(?) and Middle(?) to Late Triassic, respectively.

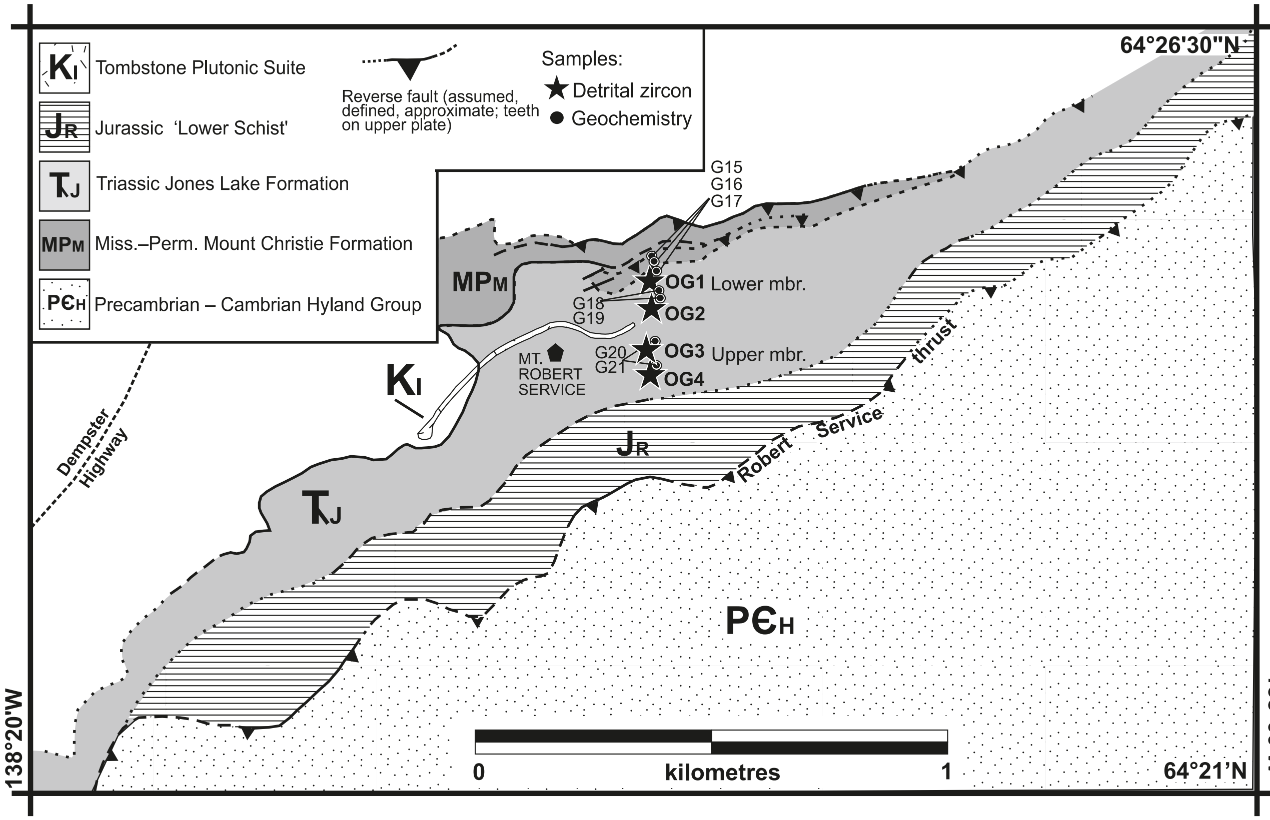
Shale samples from the Mount Christie (samples G15 and G16) and Jones Lake (samples G17–G21) formations were collected for whole-rock trace-element geochemistry (Fig. 5; Table 1). Four detrital zircon samples were selected from the Jones Lake Formation (samples OG1–OG4 in Fig. 5).[4]

Locality 3: Jones Lake Formation, Sheldon Lake map area, eastern Yukon

Late Triassic Jones Lake Formation strata lie in fault contact with Cretaceous South Fork Volcanics and Paleozoic Road River and Earn group rocks in the southwestern Sheldon Lake (NTS 105J) map area of eastern Yukon (Gordey and Irwin 1987; locality 3 in Fig. 1). Jones Lake Formation

[4] Supplementary data for this article are available on the journal Web site (cjes.nrc.ca) or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Building M-55, 1200 Montreal Road, Ottawa, ON K1A 0R6, Canada. DUD 5343. For more information on obtaining material refer to cisti-icist.nrc-cnrc.gc.ca/eng/ibp/cisti/collection/unpublished-data.html.

Fig. 5. Simplified geologic map of the Mount Robert Service region (locality 2), Ogilvie Mountains, west-central Yukon. See text for sample information and supplementary data Tables S1 and S2[4] for analytical results. mbr., member; Miss.–Perm., Mississippian – Permian. Geology from Thompson et al. (1994).



rocks at this location include grey, thickly bedded, parallel- to wavy- to ripple cross-laminated, silty to sandy to bioclastic limestone and subordinate shale and siltstone.

Late Triassic rocks in Sheldon Lake map area contain late Carnian to Rhaetian conodont fauna typical of coeval strata in the WCSB (Orchard 2006). Sandy limestone that yields Norian conodonts (Orchard 2006) was sampled for detrital zircon analysis (sample SL).

Locality 4: Hoole Formation, Quiet Lake map area, eastern Yukon

Triassic Hoole Formation strata are exposed in the Quiet Lake (NTS 105F) map area of south-central Yukon (locality 4 in Fig. 1). Hoole Formation strata occur south of the Tintina fault and are assigned to the parautochthonous Cassiar terrane (Tempelman-Kluit 1977; Tempelman-Kluit, unpublished Ram Creek map, scale 1 : 50 000).

Hoole Formation strata at locality 4 consists of tan to buff weathering, light- to medium-grey, thin to medium bedded, calcareous, muscovite-bearing, parallel- to wavy-laminated siltstone to fine-grained sandstone. These rocks contain early to late Carnian conodonts (Orchard 2006). A single sample of Hoole Formation sandstone was collected for detrital zircon analysis (sample HL).

Locality 5: Toad Formation, La Biche River map area, southeastern Yukon

Permian and Triassic siliciclastic strata crop out in the headwaters of Tika Creek in La Biche River map area (NTS 95C) of southeasternmost Yukon (locality 5 in Fig. 1). The upper portion of this section is overlain by the Cretaceous Chinkeh and Garbutt formations (Khudoley 2003). Early to Middle Triassic Toad Formation shale and sandstone occur immediately below this unconformity (Fig. 2; L. Lane, personal communication, 2009). Utting et al. (2005) concluded Toad Formation strata in an adjacent map area contain Griesbachian (early Induan) palynomorphs. Preliminary palynomorph collections from this section suggest it may be as old as Middle Permian (L. Lane and J. Utting, personal communication, 2009). A single sample of Toad Formation sandstone (sample TF) from the Tika Creek area was selected for detrital zircon analysis.

Reference frames

Numerous regional studies have utilized geochemical and isotopic data to constrain the composition and source of Neoproterozoic to Triassic continental margin strata in western Canada and eastern Alaska (e.g., Boghossian et al. 1996; Garzione et al. 1997; Gehrels and Ross 1998; Miller et al. 2006). These investigations created whole-rock trace-element, Sm–Nd isotope, and detrital zircon database, forming what we informally name the "Arctic" and "Northwest Laurentian" reference frames. Analytical results from these investigations form the foundation for our data interpretations and describe portions of Cordilleran evolution important to this study.

Table 1. Selected trace element and Nd-isotope geochemical results from North American Triassic strata of this study and Cambrian–Triassic strata in western Canada.

	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon Nd_{(t)}$	T_{DM} (Ga)	$(La/Yb)_N$	Eu/Eu*	Cr/V	Th/Sc	La/Sc	Th/Cr	Ba (ppm)
Locality 1													
Mount Christie Fm. (G1)	6.13	29.9	0.1286	—	—	—	6.98	0.671	0.51	—	—	0.09	5411
Mount Christie Fm. (G2)	5.77	31.7	0.1142	—	—	—	8.22	0.687	0.621	—	—	0.066	5937
Mount Christie Fm. (G3)	4.95	27.4	0.1133	—	—	—	8.09	0.736	0.714	—	—	0.1	3799
Mount Christie Fm. (G4)	5.5	29	0.1189	0.512063±8	–8.2	1.74	7.97	0.657	0.888	—	—	0.125	2740
Mount Christie Fm. (G5)	4.34	29.1	0.0936	—	—	—	8.49	0.609	0.409	—	—	0.11	3468
Jones Lake Fm. (G6)	6.44	39.6	0.1019	0.512009±6	–9.3	1.55	8.35	0.677	0.187	—	—	0.1	4489
Jones Lake Fm. (G7)	8.68	50.7	0.1074	—	—	—	9.93	0.637	0.751	—	—	0.118	4656
Jones Lake Fm. (G8)	5.1	30.6	0.1046	0.511960±6	–10.3	1.65	9.99	0.624	0.833	—	—	0.12	2298
Jones Lake Fm. (G9)	7.14	40.5	0.1106	—	—	—	9.8	0.661	0.902	—	—	0.115	2644
Jones Lake Fm. (G10)	7.56	41.2	0.1151	—	—	—	10.4	0.682	0.872	—	—	0.107	2022
Jones Lake Fm. (G11)	5.46	26.7	0.1281	0.512062±6	–9.1	1.93	6.41	0.635	0.855	—	—	0.16	476
Jones Lake Fm. (G12)	7	44.6	0.985	—	—	—	10.3	0.614	0.855	—	—	0.123	1024
Jones Lake Fm. (G13)	8.01	43.4	0.1157	0.511986±6	–10.1	1.8	9.61	0.639	0.833	—	—	0.127	928
Jones Lake Fm. (G14)	7.54	44	0.1075	—	—	—	9.99	0.563	0.833	—	—	0.127	886
Locality 2													
Mount Christie Fm. (G15)	3.3	15.2	0.1377	—	—	—	6.75	0.656	0.731	0.319	1.69	0.1	1205
Mount Christie Fm. (G16)	2.6	12.7	0.1298	—	—	—	6.7	0.69	0.697	0.312	1.23	0.066	5490
Jones Lake Fm. (G17)	6.7	34.1	0.1246	—	—	—	8.09	0.618	0.552	0.314	2.83	0.12	1395
Jones Lake Fm. (G18)	4.5	23.4	0.122	—	—	—	6.54	0.655	1.06	0.259	3.05	0.16	885
Jones Lake Fm. (G19)	7.7	41.1	0.1188	—	—	—	9.87	0.621	0.748	0.324	2.93	0.127	1345
Jones Lake Fm. (G20)	4.6	25	0.1167	—	—	—	7.16	0.577	1.05	0.258	2.77	0.062	1040
Jones Lake Fm. (G21)	5.3	25	0.1345	—	—	—	6.37	0.714	0.792	0.31	1.14	0.046	3380
Yukon – Northwest Territories													
Ordovician Road River Group	1.99	10.3	0.1171	0.512006±7	–7.3	1.63	5.28	0.8	0.43	0.35	1.667	0.157	616
Late Devonian Imperial Fm.	7.34	37.6	0.1181	0.512099±7	–6.8	1.61	6.64	0.79	0.49	0.461	1.51	0.082	1160
Early Mississippian Tuttle Fm.	1.65	8.43	0.1181	0.511998±8	–8.8	1.66	—	—	—	—	—	—	—
Mississippian Keno Hill Quartzite	1.76	9.65	0.1102	0.511888±6	–10.9	1.7	—	—	—	—	—	—	—
Permian Jungle Creek Fm.	4.79	27.8	0.1041	0.511966±8	–9.8	1.49	—	—	—	—	—	—	—
Permian Mount Christie Fm.	3.34	18.1	0.1116	0.512210±6	–5.4	1.24	—	—	—	—	—	—	—
British Columbia –Alberta													
Ordovician Road River Group	2.4	11.1	0.1165	0.511755±7	–12.8	2.02	14.7	0.88	0.79	0.594	2.171	0.123	1200
Late Devonian Earn Group	1.23	9.77	0.0763	0.511983±7	–7.2	1.18	9.9	1.1	0.06	0.355	2.145	0.049	2433
Permian Johnston Canyon Fm.	1.65	9.34	0.1068	0.512093±8	–7.5	1.35	—	—	—	—	—	—	—
Triassic Sulphur Mountain Fm.	4.06	21.37	0.1149	0.512136±6	–7.3	1.39	—	—	—	—	—	—	—
Triassic Sulphur Mountain Fm.	—	—	—	—	–7.5	—	—	—	—	—	—	—	—
Triassic Toad Fm.	—	—	—	—	–6.5	—	—	—	—	—	—	—	—
Triassic Toad Fm.	—	—	—	—	–10	—	—	—	—	—	—	—	—
Triassic Liard Fm.	—	—	—	—	–9.3	—	—	—	—	—	—	—	—
Triassic Liard Fm.	—	—	—	—	–8.8	—	—	—	—	—	—	—	—
Triassic Whitehorse Fm.	0.31	1.76	0.1162	0.512161±6	–6.8	1.25	—	—	—	—	—	—	—

Note: Cambrian–Permian results from Yukon and Northwest Territories are from Garzione et al. (1997); and Triassic Toad, Liard, and Whitehorse formation data in British Columbia and Alberta are from Ross et al. (1997). Second listing of Triassic Toad and Liard formation data is from Boghossian et al. (1996). Eu/Eu* = $Eu_N/(Sm_N \times Gd_N)^{1/2}$, where N is the chondrite-normalized value of Sun and McDonough (1989). Fm., Formation; ppm, parts per million; T_{DM}, depleted mantle model age. Complete analytical results for locality 1 and 2 samples are available in the supplementary data Tables S3 and S4.

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Arctic reference frame

The Arctic reference frame is restricted to Paleozoic sedimentary units in northern Alaska and Canada that contain ca. 400–680 Ma detrital zircons. Crystalline rocks of the northwestern Laurentian craton do not typically yield U–Pb zircon ages in this range; however, these detrital zircons overlap in age with early Paleozoic Caledonian magmatism in eastern Laurentia and western Baltica and Ediacaran to Cryogenian igneous activity in northern Baltica and the Arctic Alaska – Chukotka (AA in Fig. 1) terrane (e.g., Stephens and Gee 1985; Gehrels et al. 1999; Amato et al. 2009 and references therein). These exotic "Caledonian" and "Baltican" detrital zircons were incorporated into foreland basin strata during early to mid-Paleozoic Innuitian orogenesis and accretion of allochthonous terrranes against northern Laurentia. Innuitian orogenesis and related clastic wedge sedimentation in northern North America culminated in the Late Devonian to Early Mississippian Ellesmerian orogeny (Trettin et al. 1991).

Detrital zircon analysis of five Ellesmerian clastic wedge sandstone samples in the eastern Canadian Arctic Islands yielded 31 ages in the ranges 1004–1200, 1570–2002, 2250–2470, and 2620–3000 Ma (McNicoll et al. 1995). A single Silurian (424 Ma) grain was also observed in a sample of the Middle Devonian Bird Fiord Formation. McNicoll et al. (1995) suggested their Devonian clastic wedge samples were derived from the Caledonides of eastern Greenland (see Fig. 1).

Ellesmerian clastic wedge sandstone of the Late Devonian Nation River Formation in eastern Alaska produced detrital zircon ages ranging from 424–434, 1815–1838, 1874–1921, and 2653–2771 Ma (Gehrels et al. 1999). Silurian zircons were sourced from the Innuitian hinterland block in the Canadian Arctic Islands (Pearya terrane), or tectonic elements of similar Caledonian affinity, as no suitable ca. 430 Ma parent rocks are recognized to exist in western Laurentia (Gehrels et al. 1999).

Miller et al. (2006) produced a robust detrital zircon database for Triassic siliciclastic rocks overlying the Arctic Alaska – Chukotka terrane in northern Alaska and within the Sverdrup basin in the Canadian Arctic Islands. Sandstone samples from the Early Triassic Ivishak Formation along the North Slope of Alaska and Early Triassic Bjorne and Late Triassic Pat Bay formations in the Canadian Arctic Islands (Fig. 2) contained 445–490 and 500–600 Ma detrital zircons. Miller et al. (2006) suggested some of these detrital zircons were probably derived from allochthonous terranes in the Innuitian hinterland, such as the Arctic Alaska – Chukotka terrane.

Amato et al. (2009) reported >900 detrital zircon ages from 12 samples of Paleozoic metaclastic rocks overlying Arctic Alaska terrane basement on the Seward Peninsula of northwestern Alaska. Detrital zircon age peaks in these units occurred from 400–485, 510–560, 590–620, and 660–720 Ma. Amato et al. (2009) concluded that Sm–Nd isotopic geochemical data and U–Pb age constraints from 680 and 870 Ma metaigneous units indicate the pre-Neoproterozoic basement to Arctic Alaska terrane had a Late Proterozoic paleoposition near northern Baltica.

Northwest Laurentian reference frame

Continental margin rocks of the Cordilleran miogeoclinal succession in western Canada form the Northwest Laurentian reference frame (see Boghossian et al. 1996; Garzione et al. 1997; Ross et al. 1997; Gehrels and Ross 1998). Siliciclastic units from this database yield two distinct geochemical and detrital zircon profiles: (1) pre-Late Devonian strata have enriched whole-rock rare-earth element profiles (relative to chrondrite), evolved (depleted) Sm–Nd isotope geochemical signatures, and contain 1800–2000 Ma detrital zircons derived from Laurentian basement rocks in northwestern Canada; and (2) post-Late Devonian rocks have early Paleozoic (ca. 430 Ma) and Proterozoic (1000–1300, 1400–1600 Ma) detrital zircons and whole-rock Sm–Nd isotopic signatures (i.e., $\varepsilon Nd_{(t)} = -8$) interpreted to reflect mixing of both isotopically juvenile and evolved source rocks.

Post-Late Devonian Cordilleran margin strata in western Canada yield Sm–Nd isotopic ratios also observed in Ellesmerian clastic wedge deposits (Garzione et al. 1997; Ross et al. 1997). Patchett et al. (1999) suggested growth of the Innuitian orogen and its foreland basin dispersed isotopically juvenile material to the south-southwest across the Canadian Shield of northern Laurentia. This sediment was subsequently cannibalized from Ellesmerian foreland units and recycled in post-Late Devonian time to the south and west into continental margin strata in Yukon, British Columbia, and Alberta (cf. Boghossian et al. 1996; Garzione et al. 1997). The presence of ca. 430 Ma detrital zircons in Triassic strata of the WCSB indicates an ultimate source from the Innuitian hinterland (Ross et al. 1997).

Analytical methods and data presentation

U–Pb geochronology

Detrital zircons were dated using laser ablation – inductively coupled plasma – mass spectrometry (LA–ICP–MS) at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, Vancouver, British Columbia. Zircons were separated from 2–5 kg samples using standard rock crushing, Wilfley table, heavy liquid, and magnetic methods. A random portion of each of the zircon concentrates was mounted in an epoxy puck along with several grains of the 337 Ma Plešovice (Sláma et al. 2008) and 1099 Ma FC-1 (Paces and Miller 1993) standard zircons and brought to a very high polish to expose the interior of the grains. The surface of the mount was washed for 10 min with dilute nitric acid and rinsed in ultraclean water prior to analysis.

Zircons were analyzed with a New Wave UP-213 laser ablation system and Thermo-Finnigan Element 2 single collector, double-focusing, magnetic sector ICP–MS, following operating parameters similar to those described by Chang et al. (2006). Line scans rather than spot analyses were employed to minimize the effects of within-run elemental fractionation. Typically, 35% laser power and a 25 μm laser spot diameter were used. Background levels were measured with the laser off for 25 s, followed by data collection with the laser on for ∼47 s. The time-integrated signals were analyzed using the GLITTER software package described by Van Achterbergh et al. (2001) and Jackson et al. (2004), which automatically subtracts background measurements, propagates all analytical errors, and calculates isotopic ratios and ages. Corrections for mass and elemental fractionation were made by bracketing analyses of unknown grains with replicate analyses of the standard zircon. A typical analytical session consists of four analyses of the standard zircon, followed by five analyses of unknown zircons, one standard analysis, five unknown analyses, etc., and finally four standard analyses.

Interpreted ages and isotopic ratios are presented in the supplementary data Table S1[4]. Interpreted ages for grains <1000 Ma are based on calculated $^{206}Pb/^{238}U$ ages. For detrital zircons >1000 Ma, $^{207}Pb/^{206}Pb$ ages are typically used. Detrital zircons with >10% discordance were excluded from our results and age plots. Discordance was determined as the ratio between the $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ age. Detrital zircon age results are presented in the relative probability plots in Fig. 9. The plots were constructed with a Microsoft Excel macro by G.E. Gehrels at the University of Arizona, Tucson, Arizona. Detrital zircon age spectra for all samples are shown in two plots: one from 0 to 3000 Ma to show the full distribution of detrital zircon ages and one from 200 to 700 Ma to highlight the youngest detrital zircon components.

Ar–Ar geochronology

Detrital muscovite separates were hand-picked, washed in acetone, dried, wrapped in aluminum foil, and stacked in an irradiation capsule with similar-aged samples and neutron flux monitors (Fish Canyon Tuff sanidine, 28.02 Ma; Renne et al. 1998). Samples were irradiated at the McMaster Nuclear Reactor in Hamilton, Ontario, for 90 MWh, with a neutron flux of $\sim 6 \times 10^{13}$ neutrons/cm^2/s. Analyses (n = 48) of 16 neutron flux monitor positions produced errors of <0.5% in the J value.

The samples were analyzed at the Noble Gas Laboratory at the PCIGR. Mineral separates were step-heated at incrementally higher powers in the defocused beam of a 10W CO_2 laser (New Wave Research MIR10) until fused. The gas evolved from each step was analyzed by a VG5400 mass spectrometer equipped with an ion-counting electron multiplier. All measurements were corrected for total system blank, mass spectrometer sensitivity, mass discrimination, radioactive decay during and subsequent to irradiation, as well as interference from atmospheric Ar contamination and the irradiation of Ca, Cl, and K (isotope production ratios: $(^{40}Ar/^{39}Ar)_K = 0.0302 \pm 0.00006$, $(^{37}Ar/^{39}Ar)_{Ca} = 1416.4 \pm 0.5$, $(^{36}Ar/^{39}Ar)_{Ca} = 0.3952 \pm 0.0004$, Ca/K = 1.83 ± 0.01 $(^{37}Ar_{Ca}/^{39}Ar_K)$).

Both plateau and integrated ages are reported because detrital muscovite grains were too fine grained to analyze individually. The plateau age is the error-weighted mean of the heating steps comprising the plateau, whereas the integrated age is the volume-weighted mean of all the steps calculated by recombining the isotopic measurements of all the heating steps. Ages were calculated with the Isoplot 3.0 Microsoft Excel macro (Ludwig 2003) and are listed in supplementary data Table S2[4]. Errors are quoted at the 2σ (95% confidence) level and propagated from all sources except mass spectrometer sensitivity and age of the flux monitor.

Whole-rock trace element and Nd-isotope geochemistry

Twenty-one samples of shale to silty shale were analyzed for whole-rock trace and rare-earth element geochemistry at the ALS Chemex laboratories in North Vancouver, British Columbia. Geochemical data were collected by inductively coupled plasma – atomic emission (ICP–AES) and ICP–MS. Analytical results are presented the supplementary data Table S3[4].

Five samples from the suite were selected for whole-rock Nd-isotope geochemistry at the PCIGR using thermal ionization mass spectrometry (TIMS) following the dissolution and analytical methods of Pretorius et al. (2006) and Weis et al. (2006). Nd-isotope data are presented relative to the La Jolla standard, with an analytical uncertainty of 0.511852 ± 0.000015 (2σ), and listed in the supplementary data Table S4[4]. Conversion of initial $^{143}Nd/^{144}Nd$ ratios into εNd values and depleted mantle model ages (T_{DM}) were calculated by equations defined in DePaolo (1981).

Conodont fossil collections

Mount Christie Formation stratotype

Red-weathering limestone $\sim$200 m beneath the top of the Mount Christie Formation type section yielded the early Artinskian (Early Permian) taxa *Mesogondolella bisselli* (Clark and Behnken) and *Sweetognathus inornatus* Ritter (Geological Survey of Canada (GSC) curation number C-307444, Fig. 4; Fig. 6). These conodonts were previously observed in Mount Christie Formation rocks at the type section and other localities in eastern Yukon (Orchard 2006). The colour alteration index (CAI) for these conodonts ranged from 4.5 to 5.5.

Sweetognathus is rare in continental margin rocks of Yukon but observed with *Mesogondolella bisselli* in Slide Mountain terrane strata of northern British Columbia and type Harper Ranch Group of Quesnellia (Orchard 1991). Elsewhere, Mount Christie Formation rocks also contain the late Artinskian *Neostreptognathodus pequopensis* Behnken, which occurs in Slide Mountain terrane strata of southeastern Yukon (Murphy et al. 2006; Orchard 2006).

Jones Lake Formation stratoype

Conodonts were only retrieved from the lowermost 340 m of the Jones Lake Formation type section (Fig. 4). Therefore, the age of the entire upper member remains unconstrained. CAI values for all collections ranged from 4.5 to 5.0.

Calcareous sandstone collected $\sim$75 m above the base of the formation contained the late Induan – early Olenekian (Dienerian–Smithian) conodonts *Scythogondolella*? sp. and *Neospathodus dieneri* Sweet (GSC C-307445, Fig. 4; Fig. 6). The latter conodont is a cosmopolitan Dienerian species in the Cordillera, which has been described from Triassic strata of the WCSB in the Wapiti Lake area of northeastern British Columbia (Orchard and Zonneveld 2009) and Cache Creek terrane in southern British Columbia (Orchard 1991). This Jones Lake Formation collection also contained reworked fragments of Devonian *Icriodus* sp. and Permian *Mesogondolella*? sp. (Fig. 6).

Calcareous siltstone sampled $\sim$45 m above the

Dienerian–Smithian collection contained the early Olenekian conodonts *Borinella chowadensis* Orchard, *Discretella discreta* (Muller), *Neospathodus* cf. *pakistansensis* Sweet, and *Ns.* cf. *posterolongatus* Zhao and Orchard (GSC C-307446, Fig. 4; Fig. 6). All of these conodonts are recognized in Triassic strata of the WCSB in northeastern British Columbia (Orchard 2007; Orchard and Zonneveld 2009). Reworked Late Mississippian *Gnathodus* cf. *girtyi* Hass and Early Permian *Mesogondolella* sp. are also present (Fig. 6). *Neospathodus pakistansensis* has been identified in the Sverdrup basin in the Canadian Arctic Islands (Orchard 2008) and Mesozoic rocks of Stikinia (Orchard 1991). Poorly preserved neospathodids of probably Early Triassic age have also been observed in the Nicola Group of Quesnellia (Orchard 1991).

Sandy limestone collected from the base of the upper member, which had previously yielded Smithian fauna (Orchard 1991; Gordey and Anderson 1993), contained the mid-Smithian conodonts *Neospathodus posterolongatus*, *Ns. pakistanensis*, *Ns. waageni* Sweet, *Scythogondolella*? aff. *crenulata* (Mosher), *S. mosheri* (Kozur and Mostler), *S. phryna* Orchard, *Borinella chowadensis*, and *Wapitiodus robustus* Orchard (GSC C-307447, Fig. 4; Fig. 6). Reworked Pennsylvanian species of *Idiognathodus*, *Idiognathoides*, and *Rhachistognathus*, and Permian *Mesogondolella* were also present (Fig. 6). Most of the conodonts in this sandy limestone horizon are widespread in Lower Triassic strata of the WCSB and the Sverdrup basin in the Canadian Arctic Islands (Orchard 1991, 2006), where most are best known in association with ammonoids of the *Euflemingites romunduri* Zone (Orchard 2008; Orchard and Zonneveld 2009). Orchard (2006) noted reworked Induan conodonts *Neogondolella* ex gr. *carinata* (Clark) and *Neospathodus dieneri* Sweet from this stratigraphic horizon.

Whole-rock provenance results and correlations

Mount Christie Formation

Whole-rock geochemical samples of Mount Christie Formation shale yielded enriched rare-earth element (REE) patterns ($(La/Yb)_N = \sim 7.0$) and negative europium anomalies ($Eu/Eu^* = \sim 0.66$) that indicate a partial source from granitic, upper crustal rocks (McLennan et al. 2003; Figs. 7A, 8A; Table 1). These signatures are widely recognized in Paleozoic Cordilleran margin strata and interpreted to reflect a cratonal source from Precambrian rocks and their sedimentary derivatives in western Canada (Garzione et al. 1997).

Trace-element ratios from localities 1 and 2 generally show enrichments in relatively compatible, ferromagnesian elements such as Co, V, Sc, and Cr upsection towards the Jones Lake Formation (see Table 1; Figs. 7C–7F, 8C–8F). These signatures most likely indicate addition of mineral phases, such as chromite, ultimately derived from mafic or ultramafic igneous rocks (McLennan et al. 2003).

The high barium content of Mount Christie Formation rocks (up to 5490 parts per million (ppm)) reflects the presence of barite nodules observed in outcrop at the stratotype location (Table 1). Regionally, the underlying Late Devonian to Early Mississippian Earn Group contains stratiform barite horizons and high barium concentrations (Garzione et al. 1997). Recycling of these rocks during the Mississippian to Permian may account for elevated Mount Christie Formation barium contents.

Whole-rock Nd-isotope geochemical analysis of a single Mount Christie Formation sample yielded an $\varepsilon Nd_{(275\ Ma)}$ value of –8.2, which is consistent with other post-Devonian strata in western Canada (Table 1; Garzione et al. 1997). Permian strata in the Canadian Arctic Islands produced $\varepsilon Nd_{(t)}$ values ranging from –7.9 to –10.4 (Patchett et al. 2004). Garzione et al. (1997) attributed the Nd-isotopic signatures of Permian shales in Yukon and northern British Columbia to reflect the recycling of Ellesmerian clastic wedge sediment into the northern Cordilleran miogeocline (cf. Patchett et al. 1999, 2004).

Jones Lake Formation

Jones Lake Formation shale samples display enriched REE signatures ($(La/Yb)_N = \sim 8$) and negative Eu anomalies ($Eu/Eu^* = \sim 0.66$) representative of an upper crustal source (McLennan et al. 2003; Figs. 7B, 8B; Table 1). Similar to the underlying Mount Christie Formation, samples of Jones Lake Formation shale yield REE values recorded in Paleozoic Cordilleran margin strata (Table 1).

Jones Lake Formation rocks from localities 1 and 2 generally have elevated Cr, Ni, and Co values relative to the underlying Mount Christie Formation (see Table 1; Figs. 7C–7F, 8C–8F). These data support the interpretation that some Early Triassic strata in Yukon were derived, in part, from ferromagnesian, mafic source rocks. The provenance of this mafic detritus is not constrained; however, these trace-element signatures may be attributed to a source from early Paleozoic alkaline volcanic rocks in eastern Yukon (see Goodfellow et al. 1995; Garzione et al. 1997) or mafic igneous rocks residing in Cordilleran terranes to the west that overrode the North American margin in Late Permian – Early Triassic time (Nelson et al. 2006; Colpron et al. 2007). Barium concentrations up to $\sim$4500 ppm in the Triassic units (Table 1) suggest recycling of older Paleozoic strata, including the Mount Christie Formation. This erosion and recycling is consistent with the presence of older, reworked conodont elements observed in North American Triassic strata (Orchard 1991, 2006) and sub-Triassic unconformities in the Little Nahanni River and Dawson map areas.

Epsilon Nd-isotope values for the Jones Lake Formation stratotype shale samples at the time of deposition ($\sim$248 Ma) range from –10.1 to –9.1, which compare favorably with Early to Late Triassic strata of the WCSB in British Columbia and Alberta (Table 1; Boghossian et al. 1996; Ross et al. 1997). Patchett et al. (2004) reported similar results in which Early, Middle, and Late Triassic strata in the Canadian Arctic Islands yield $\varepsilon Nd_{(t)}$ values from –6 to –11, –8.4 to –10, and –2.9 to –10.3, respectively. Boghossian et al. (1996) and Ross et al. (1997) hypothesized a mixed Ellesmerian–Laurentian source for the Triassic Toad, Liard, Sulphur Mountain, and Whitehorse formations in British Columbia and Alberta to explain their Nd-isotope data (cf. Patchett et al. 1999).

Fig. 6. Photomicrographs of Devonian to Triassic conodont fossils described in this study. Stratigraphic positions of collections indicated by Geological Survey of Canada (GSC) curation numbers (see Fig. 4). Numbers 8–14 from the Mount Christie Formation (GSC locality (loc.) C-307444), others from Jones Lake Formation (GSC loc. C-307447, unless stated otherwise). Scale bar = 200 µm (all figures ×80). (**1**) *Icriodus* sp. indet., GSC 131179; GSC loc. C-307445; (**2, 3**) *Rhachistognathus* cf. *proxilus* Baesemann and Lane, GSC 131180; (**4**) *Idiognathodus delicatus* Gunnell, GSC 131181; (**5**) *Idiognathoides sinuatus* Harris and Hollingsworth, GSC 131182; (**6**) *Gnathodus* cf. *girtyi* Hass, GSC 131183; GSC loc. C-307446; (**7**) *Idiognathoides pacificus* Savage and Barkeley, GSC 131184; (**8–11, 14**) *Mesogondolella bisselli* (Clark and Behnken); (8, 14) GSC 131185; (9–11) GSC 131186; (**12, 13**) *Sweetognathus inornatus* Ritter, GSC 131187; (**15–17**) *Wapitiodus robustus* Orchard, GSC 131188; (**18, 19**) *Discretella discreta* (Muller), GSC 131189; GSC loc. C-307446; (**20, 21**) *Neospathodus dieneri* Sweet, GSC 131190; GSC loc. C-307445; (**22, 23**) *Neospathodus waageni* Sweet, GSC 131191; (**24, 25**) *Neospathodus posterolongatus* Zhao and Orchard, GSC 131192; (**26–28**) *Scythogondolella mosheri* (Kozur and Mostler), GSC 131193; (**29, 30**) *Scythogondolella*? aff. *crenulata* (Mosher), GSC 131194; (**31–33**) *Neospathodus pakistanensis* Sweet, GSC 131195; (**34–36**) *Borinella chowadensis* Orchard, GSC loc. C-307446; (**37–39**) *Scythogondolella phryna* Orchard and Zonneveld, GSC 131197.

Detrital mineral age results and correlations

Locality 1: Mount Christie and Jones Lake formation stratotypes

Detrital zircon geochronology

Jones Lake Formation type section sandstones contain numerous detrital zircon age peaks that occur in rocks of the Northwest Laurentian and Arctic reference frames. For example, locality 1 samples JL1 and JL2 display late Paleoproterozoic and Archean ages (25%; 47 of 182 grains) with peaks at 1745, 1834, 1837, 1997, and 2640 Ma (Figs. 9A, 9B) observed in Neoproterozoic to Triassic WCSB strata (Figs. 9K–9M; Ross et al. 1997; Gehrels and Ross 1998) and Triassic formations in northern Alaska and the Canadian Arctic Islands (Figs. 9O–9Q; Miller et al. 2006). Early Mesoproterozoic to late Paleoproterozoic ages (18%; 34 of 182 grains) in samples JL1 and JL2, with peaks at 1423, 1474, and 1650 Ma, are not typically recognized in WCSB strata but overlap with detrital zircon ages in the Proterozoic Pinguicula Group of northern Yukon (Rainbird et al. 1997) and Triassic rocks of the Canadian Arctic Islands (Fig. 9P, 9Q; Miller et al. 2006).

Samples JL1 and JL2 contain abundant early Paleozoic to Neoproterozoic age peaks, the majority of which have not been observed in the North American reference frame for western Canada (Figs. 9K–9M). This may be an artifact of smaller sample size and isotope-dilution analytical technique (ID–TIMS) employed by previous studies (e.g., Gehrels and Ross 1998). Peaks at 414, 433, 437, 451, 478, 524, and 671 Ma correlate with "Caledonian" and "Baltican" age occurrences in the Arctic reference frame (Figs. 9N–9Q), including the Late Devonian Nation River Formation of eastern Alaska (Gehrels et al. 1999) and Triassic strata of northern Alaska and Canadian Arctic Islands (Miller et al. 2006). Early Paleozoic to Neoproterozoic (ca. 400–700 Ma) ages in samples JL1 and JL2 contained 10 of 25 (40%) and 27 of 157 (17%) zircon grains, respectively, in each sample. Occurrences from 400–475 Ma were the most abundant within the 400–700 Ma age field, combining for 19 of 37 grains (51%). Single-grain occurrences at ca. 430 Ma were observed in the Pennsylvanian to Triassic portion of the North American reference frame in western Canada (Figs. 9L, 9M; Ross et al. 1997; Gehrels and Ross 1998).

A single 338 Ma zircon was observed in sample JL2. This age is notable because Mississippian igneous rocks are not recognized within autochthonous North America in western Canada; however, a well-documented pulse of magmatism of this age occurs in the adjacent, but allochthonous Yukon–Tanana terrane (Colpron et al. 2006).

Detrital muscovite geochronology

Fine-grained detrital muscovite from two samples at locality 1 yielded poorly constrained ages because the crystals expelled very little gas during incremental heating, typically with the bulk of the argon evolved in one or two steps. Therefore, we use the more conservative integrated age, rather than plateau age, in our interpretations.

Samples collected from the Mount Christie and Jones Lake type sections yielded integrated ages at 430 ± 47 Ma (plateau age at 436 ± 28 Ma) and 360 ± 35 Ma (plateau age at 363 ± 26 Ma), respectively. These ages may overlap when accounting for analytical error. Paleozoic muscovite-bearing igneous or metamorphic rock units are not typically recognized within the Laurentian autochthon of northwestern Canada; however, Late Devonian to Early Mississippian (ca. 360 Ma) deformation and metamorphism affected Yukon–Tanana terrane rocks in western, central, and southeastern Yukon (Murphy et al. 2006; Berman et al. 2007). For example, Devine et al. (2006) demonstrated muscovite in Yukon–Tanana terrane rocks in southeastern Yukon, presently ~200 km southwest of locality 1, yield single-crystal Ar–Ar ages at 353 Ma. The ca. 430 Ma Ar–Ar muscovite age for the Mount Christie Formation is in agreement with the ca. 435 Ma detrital zircon age peaks in Jones Lake Formation type section rocks and in Devonian to Triassic strata which comprise the Arctic reference frame in northern Alaska and Canadian Arctic Islands (Figs. 9N–9Q; Gehrels et al. 1999; Miller et al. 2006).

Locality 2: Jones Lake Formation, Ogilvie Mountains

Jones Lake Formation sandstone samples (OG1–OG4) at locality 2 yield Paleoproterozoic and Archean age peaks (Figs. 9C–9F) observed within Neoproterozoic to Triassic strata of the Northwest Laurentian and Arctic reference frames (Figs. 9K–9Q; Ross et al. 1997; Gehrels and Ross 1998; Gehrels et al. 1999; Miller et al. 2006). Occurrences of ca. 1800–3000 Ma detrital zircon in both the lower (samples OG1 and OG2) and upper (samples OG3 and OG4) members are consistent with those at the Jones Lake type section, averaging ~27% of each sample.

Meso- to Paleoproterozoic ages from ca. 1400–1650 Ma, with peaks at 1409, 1500, 1622, and 1627 Ma, are present

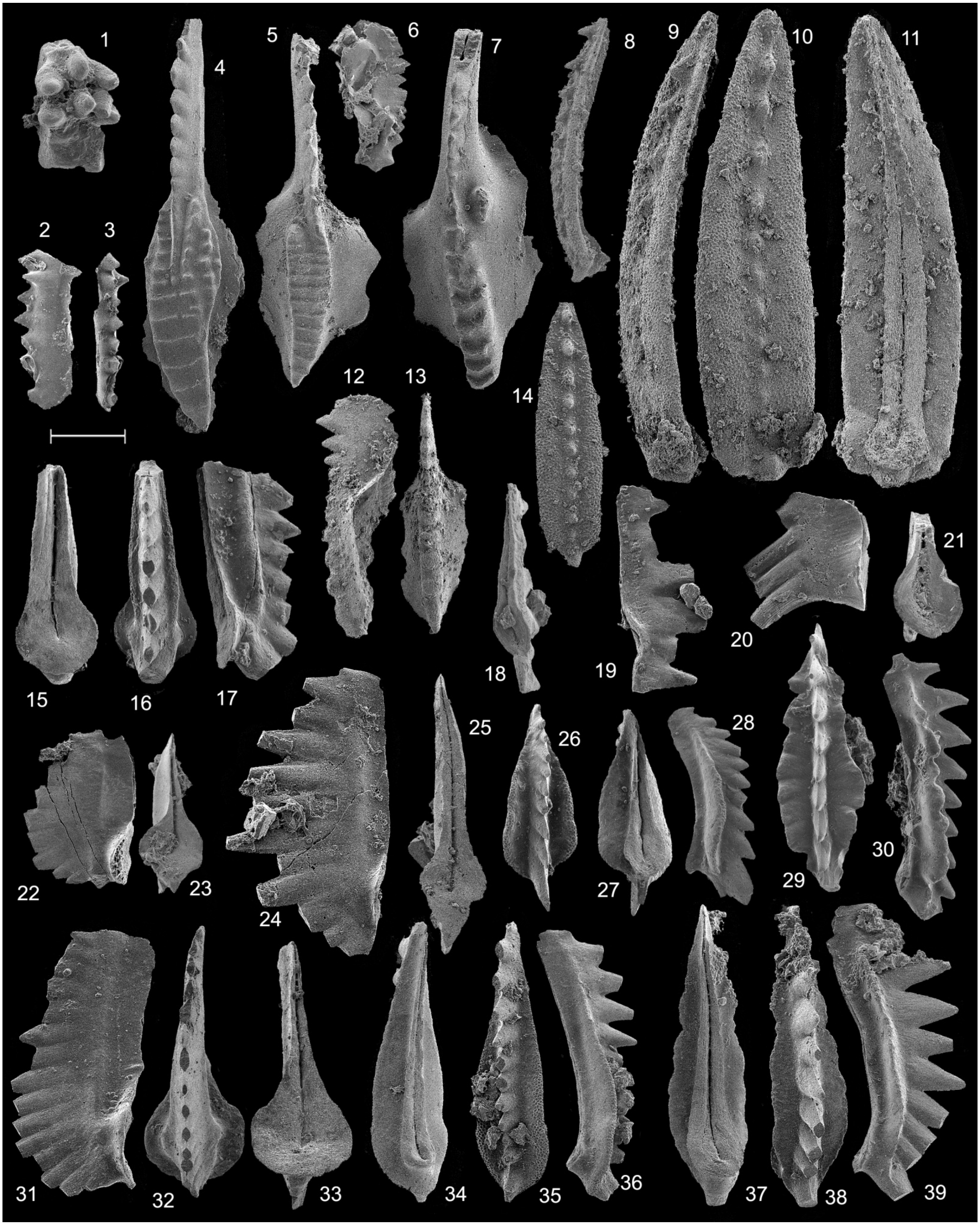
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Fig. 7. Trace-element geochemical data from samples of Mount Christie and Jones Lake formation shale at their type section. (A) Chondrite-normalized rare-earth element (REE) pattern for Mount Christie Formation samples; (B) chondrite-normalized REE pattern for Jones Lake Formation samples; (C) Co (ppm) versus La/Co; (D) La/Yb versus Cr (ppm) + Ni (ppm); (E) Ni/V versus Cr/V; (F) Cr/V versus Cr/Ni. FM., Formation; Loc., locality; ppm, parts per million.

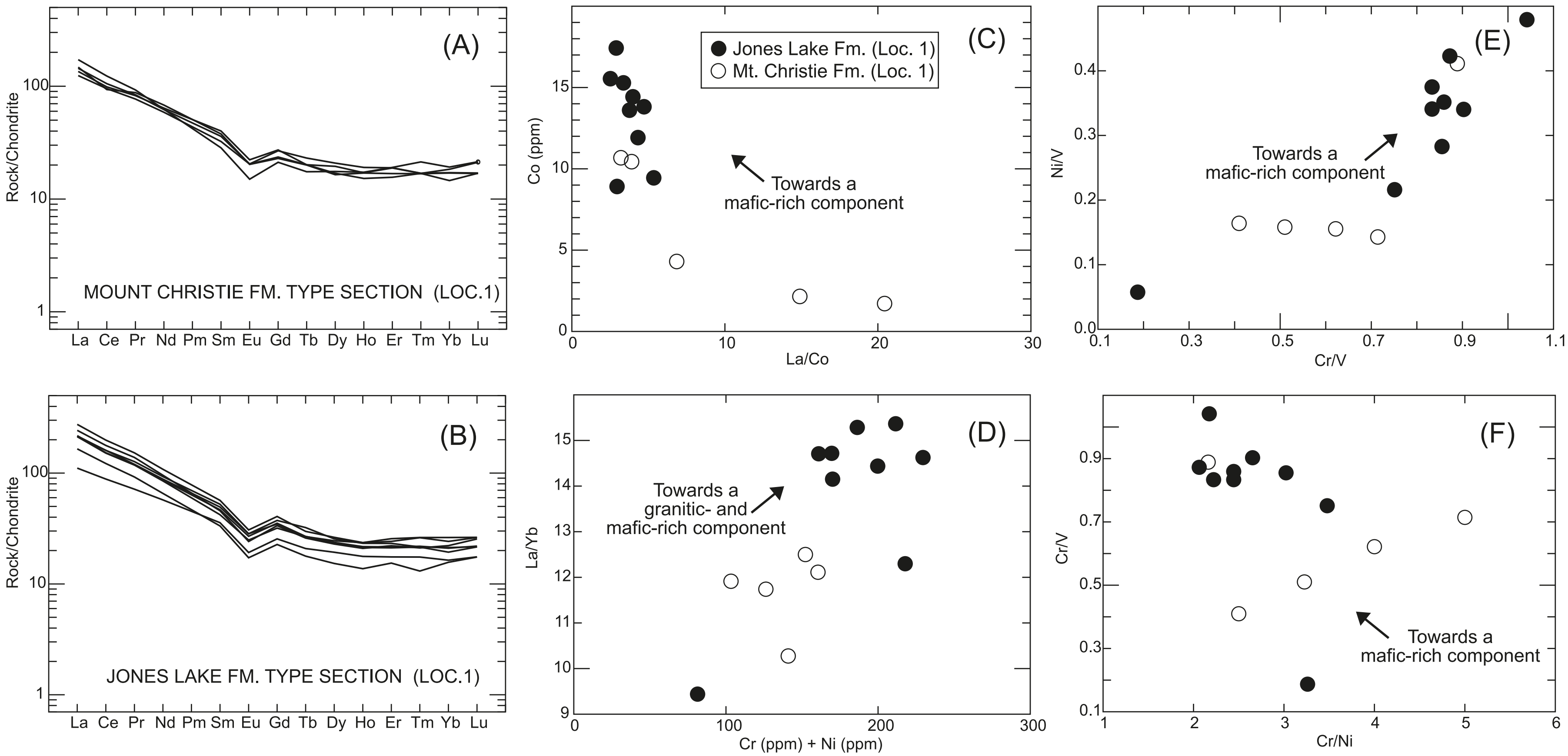

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Fig. 8. Trace-element geochemical data from samples of Mount Christie and Jones Lake formation shale at locality 2 in west-central Yukon. (A) Chondrite-normalized rare-earth element (REE) pattern for Mount Christie Formation samples; (B) chondrite-normalized REE pattern for Jones Lake Formation samples; (C) Co (ppm) versus La/Co; (D) La/Yb versus Cr (ppm) + Ni (ppm); (E) Ni/V versus Cr/V; (F) Cr/V versus Cr/Ni. FM., Formation; Loc., locality; ppm, parts per million.

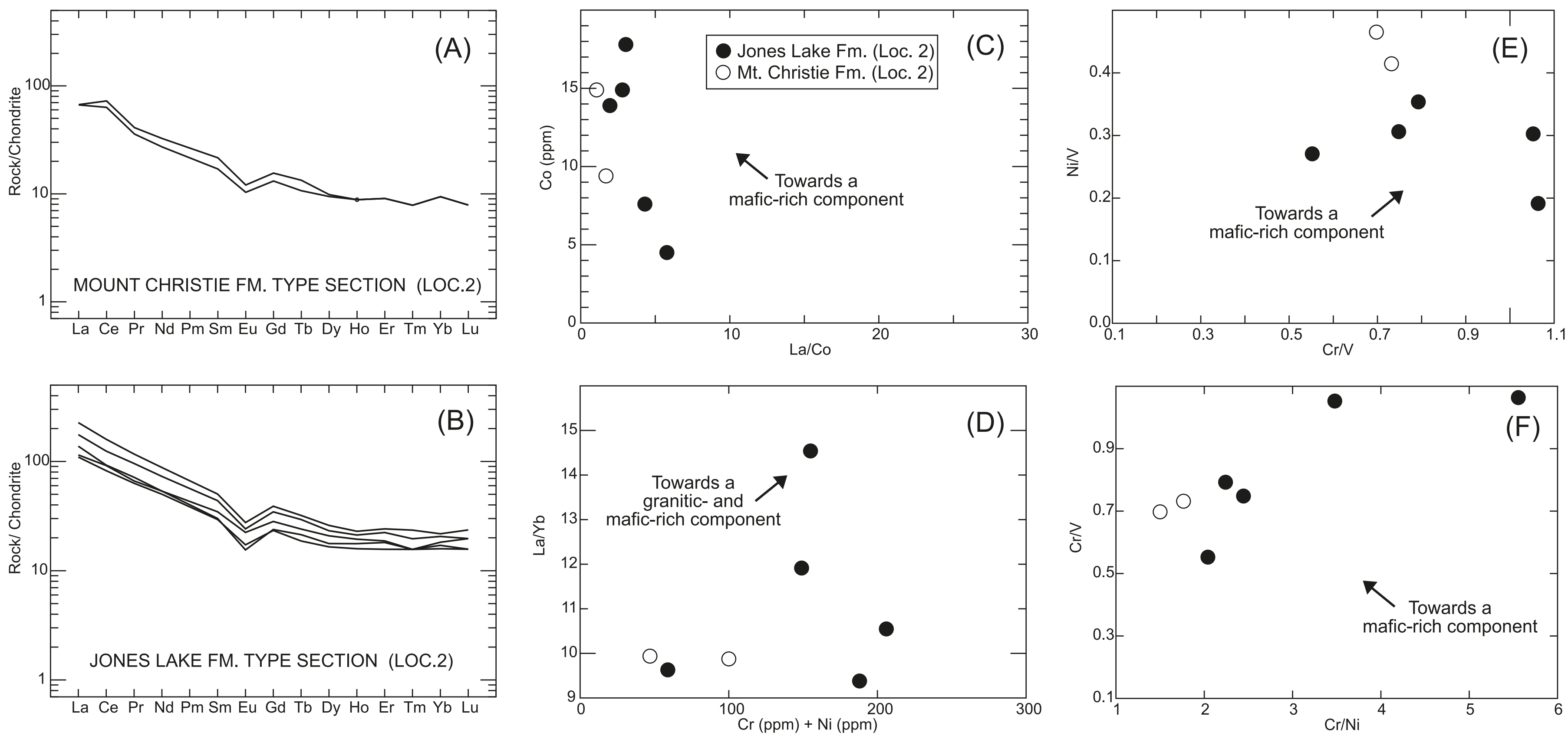


Fig. 9. Relative age probability plots (0–3000 and 200–700 Ma) for U–Pb detrital zircon data. The probability curve for each sample is normalized to the total number of detrital zircon grains reported. Interpreted ages are available in the supplementary data Table S1[4]. (A) Sample JL1 from locality (loc.) 1; (B) sample JL2 from loc. 1; (C) sample OG1 from loc. 2; (D) sample OG2 from loc. 2; (E) sample OG3 from loc. 2; (F) sample OG4 from loc. 2; (G) sample SL from loc. 3; (H) sample HF from loc. 4; (I) sample TF from loc. 5; (J) composite signature for all detrital zircons displayed in Figs. 9A–9L; (K) Neoproterozoic to Cambrian WCSB strata, Alberta and British Columbia (B.C.) (Gehrels and Ross 1998); (L) Pennsylvanian to Permian WCSB strata, Alberta and B.C. (Gehrels and Ross 1998); (M) Middle and Late Triassic WCSB strata, B.C. (Ross et al. 1997); (N) Late Devonian Nation River Formation, eastern Alaska (Gehrels et al. 1999); (O) Early Triassic Ivishak Formation, North Slope, northern Alaska (Miller et al. 2006); (P) Late Triassic Pat Bay Formation, Sverdrup basin, Canadian Arctic Islands (Miller et al. 2006); (Q) Early Triassic Bjorne Formation, Sverdrup basin, Canadian Arctic Islands (Miller et al. 2006). Grey bar in 0–3000 Ma plots indicates the age range of Paleoproterozoic cratonal rocks in northwestern Laurentia (Hoffman 1988). Grey bars in 200–700 Ma plots display, from left to right, the age ranges of Paleozoic magmatism on the Yukon–Tanana terrane (Colpron et al. 2006), Caledonian magmatism, and Arctic Alaska detrital zircon results and magmatism on the paleocontinent Baltica (Amato et al. 2009 and references therein). Fm., Formation; *n*, number of samples.

at a ~13% level (30 of 229 grains) in most samples. Detrital zircons with these ages are observed in Proterozoic Pinguicula Group and Wernecke Supergroup rocks in northern Yukon (Rainbird et al. 1997; Furlanetto et al. 2009). Meso- to Neoproterozoic age peaks from ca. 950–1150 Ma correspond with Pennsylvanian to Triassic strata of the Northwest Laurentian and Arctic reference frames (Figs. 9L, 9M, 9O–9Q; Gehrels and Ross 1998; Miller et al. 2006). Overall, 950–1150 Ma detrital zircons average ~13% within all samples at locality 2.

Samples OG2–OG4 contain 400–480 Ma grains at a 15% level (33 of 201 grains) and 530–680 Ma ages occur in all collections, averaging out to ~9% (21 of 229 grains) of each sample. Detrital zircon ages from ca. 360–390 Ma can be correlated to Middle to Late Devonian intrusive rocks emplaced into the Pearya terrane (Trettin et al. 1987) and the Ellesmerian foreland in northern Yukon (Lane 2007).

A single 350 Ma detrital zircon was observed in sample OG4. Along with the 338 Ma detrital zircon at locality 1, this age cannot be correlated with any North American source rocks in northwestern Canada but is in agreement with published U–Pb results from igneous rocks of Yukon–Tanana terrane (Colpron et al. 2006). A single-grain occurrence has statistical limitations; however, the presence of Mississippian zircon and the micaceous nature of Jones Lake Formation strata at localities 1 and 2 are most consistent with an outboard source from the Yukon–Tanana terrane.

Locality 3: Jones Lake Formation, Sheldon Lake map area

Late Triassic sandy limestone (sample SL) in eastern Yukon produced detrital zircon signatures that are mostly compatible with Jones Lake Formation samples at localities 1 and 2 (Fig. 9G). Early Neoproterozoic to Archean detrital zircons form over 65% of sample SL (40 of 61 grains) with age groupings at ca. 950–1150 Ma (29%; 18 grains), 1400–1650 Ma (9%; 6 grains), and 1800–2700 Ma (13%; 8 grains). Paleo- to Mesoproterozoic age peaks at 1432 and 1661 Ma compare with those in the Proterozoic Pinguicula Group in the Ogilvie Mountains (Rainbird et al. 1997) and Triassic Bjorne Formation in the Canadian Arctic Islands (Fig. 9Q; Miller et al. 2006).

Early Paleozoic (ca. 400–430 Ma) and late Neoproterozoic (520–650 Ma) ages form 13% and 16% of sample SL, respectively. Age peaks observed in sample SL at 414 and 427 Ma generally correspond to Devonian to Triassic strata of the Arctic reference frame (Figs. 9N–9Q; Gehrels et al. 1999; Miller et al. 2006).

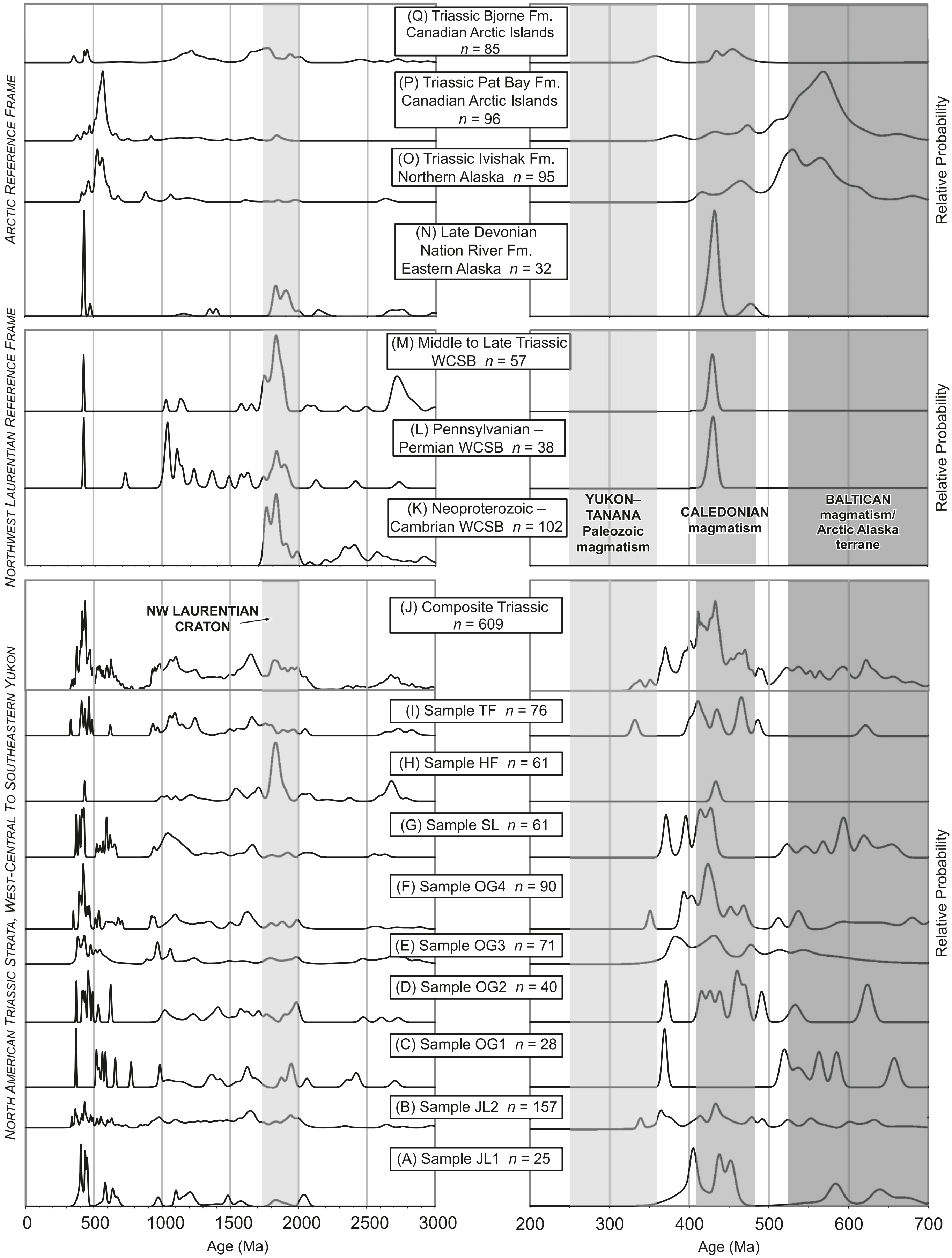
Locality 4: Hoole Formation, Quiet Lake map area

Detrital zircon analysis of Hoole Formation sandstone (sample HL) indicates Late Triassic strata of the parautochthonous Cassiar terrane have a similar provenance to Jones Lake Formation and WCSB rocks of the North American autochthon. However, Precambrian detrital zircons in sample HL appear to be in larger concentration compared with other sandstone samples analyzed by this study. For example, a dominant Paleoproterozoic and Archean zircon component (75%; 46 of 61 grains) and 1500–1580 Ma ages (9%; 6 grains) give sample HL a distinctive spectral profile, displayed by peaks at 1836, 2027, and 2677 Ma (Fig. 9H). These 1800–2700 Ma peaks are similar to those reported in Neoproterozoic to Triassic strata of the Northwest Laurentian reference frame (Figs. 9K–9M; Ross et al. 1997; Gehrels and Ross 1998). The prevalence of 1800–2700 Ma detrital zircons in sample HF may indicate Triassic Cassiar terrane strata, which are now southwest of the Tintina fault, display an original latitudinal control on the distribution of Precambrian age populations or a lack of dilution by early Paleozoic – Neoproterozoic grains. A single 433 Ma detrital zircon was observed in sample HF.

Locality 5: Toad Formation, La Biche River map area

Toad Formation sandstone (Fig. 9I) from southeasternmost Yukon shares detrital zircon ages with continental margin strata in Alaska and western Canada. Early Proterozoic to Archean ages in sample TF (31%; 24 of 76 grains), with peaks at 1758, 1803, 1889, 1969, and 2728 Ma, characterize detrital zircon occurrences in Neoproterozoic to Triassic strata of the WCSB (Figs. 9K–9M; Ross et al. 1997; Gehrels and Ross 1998) and the Triassic Bjorne Formation in the Canadian Arctic Islands (Fig. 9Q; Miller et al. 2006). Proterozoic detrital zircon ages ranging from 950–1300 Ma (31%; 24 of 76 grains) and 1400–1650 Ma (14%; 11 of 76 grains) yielded peaks at 1058–1242, 1589, and 1657 Ma, corresponding to Proterozoic Pinguicula Group strata (Rainbird et al. 1997) in northern Yukon and Pennsylvanian to Triassic strata of the Northwest Laurentian and Arctic reference frames (Figs. 9L, 9M, 9O–9Q; McNicoll et al. 1995; Gehrels and Ross 1998; Miller et al. 2006).

Early Paleozoic (400–480 Ma) detrital zircon ages in sam-



(Q) Triassic Bjorne Fm.
Canadian Arctic Islands
n = 85
(P) Triassic Pat Bay Fm.
Canadian Arctic Islands
n = 96
(O) Triassic Ivishak Fm.
Northern Alaska n = 95
(N) Late Devonian
Nation River Fm.
Eastern Alaska n = 32
ARCTIC REFERENCE FRAME
(M) Middle to Late Triassic
WCSB n = 57
(L) Pennsylvanian –
Permian WCSB n = 38
(K) Neoproterozoic –
Cambrian WCSB n = 102
NORTHWEST LAURENTIAN REFERENCE FRAME
YUKON–
TANANA
Paleozoic
magmatism
CALEDONIAN
magmatism
BALTICAN
magmatism/
Arctic Alaska
terrane
NW LAURENTIAN
CRATON
(J) Composite Triassic
n = 609
(I) Sample TF n = 76
(H) Sample HF n = 61
(G) Sample SL n = 61
(F) Sample OG4 n = 90
(E) Sample OG3 n = 71
(D) Sample OG2 n = 40
(C) Sample OG1 n = 28
(B) Sample JL2 n = 157
(A) Sample JL1 n = 25
NORTH AMERICAN TRIASSIC STRATA, WEST-CENTRAL TO SOUTHEASTERN YUKON
Relative Probability
Relative Probability
Relative Probability
0
500
1000
1500
2000
2500
3000
Age (Ma)
200
300
400
500
600
700
Age (Ma)

ple TF occur at a 13% level (10 of 76 grains) and include a 465 Ma peak recognized in Early Triassic Ivishak Formation sandstone (Fig. 9Q; Miller et al. 2006). The Middle Ordovician age also correlates with 463 Ma intrusive rocks known to the Pearya terrane (Trettin et al. 1987). Multiple Paleozoic single-grain ages at 401, ca. 410, and ca. 435 Ma are similar to age peaks in other North American Triassic rocks in Yukon. The Toad Formation contains a single 331 Ma zircon; as with the occurrence of Mississippian grains in Jones Lake Formation strata, this age corresponds with Yukon–Tanana terrane igneous rocks in Yukon (Colpron et al. 2006).

Conclusions

The sampling of continental margin strata at five localities in Yukon generated the first detrital zircon age, detrital muscovite age, and whole-rock trace-element and Nd-isotope geochemical reference frames for North American Triassic rocks in the northern Canadian Cordillera. Provenance results and regional correlations support the following conclusions:

(1) Early to Late Triassic North American strata from west-central to southeastern Yukon have reproducible detrital zircon age and whole-rock geochemical signatures. The composite Triassic detrital zircon signature for all samples in Fig. 9J contains prominent age peaks at ca. 410, 430, 470, 530–620, 980, 1100, 1650, 1830, and 2680 Ma. Comparison of the individual Triassic samples (Figs. 9A–9I) with the composite Triassic signature (Fig. 9J) generally indicates that depositional age and lithology do not significantly affect the occurrence of specific detrital zircon ages. For example, Early Triassic micaceous sandstone at locality 1 (Fig. 9B) and Late Triassic sandy limestone at locality 3 (Fig. 9G) shared early Paleozoic and Precambrian detrital zircon ages. However, the relative nonconformity in age peaks between closely spaced samples at one location (i.e., Figs. 9A–9F) may suggest local changes in sedimentary source or that the sedimentary environments were not well-mixed.

(2) Whole-rock geochemical signatures, reworked conodont fossils, and recycled detrital zircons demonstrate Triassic strata in Yukon are primarily derived from the cannibalization of Paleozoic (and in some cases Triassic) sedimentary rocks in northwestern Laurentia. Early Paleozoic to Neoproterozoic (ca. 400–680 Ma) and Meso- to Paleoproterozoic (1000–2000 Ma) detrital zircon age peaks are significant in North American Triassic rocks, similar to post-Late Devonian strata of the Northwest Laurentian and Arctic reference frames (e.g., Gehrels et al. 1999; Miller et al. 2006). The age ranges of Caledonian and Baltican magmatism, including that of the Arctic Alaska – Chukotka terrane, overlap well with the peaks from ca. 400–680 Ma (see grey bars in Fig. 9; Amato et al. 2009 and references therein). Detrital zircons recycled from Innuitian (Ellesmerian) clastic wedge strata are, therefore, an important component in Triassic continental margin rocks (see Figs. 9J, 9M, 9O–9Q). Paleoproterozoic ages correspond to Neoproterozoic to Triassic miogeoclinal strata in western Canada and crystalline rocks of the northwest Laurentian craton in Canada (see grey bar in Fig. 9; Hoffman 1988).

(3) North American Triassic strata in Yukon have undisputed conodont fossil, detrital zircon age, and whole-rock geochemical linkages with coeval WCSB rocks in British Columbia and Alberta. Strong conodont and provenance correlations also exist between Triassic strata in Yukon and Triassic rocks in the Sverdrup basin in the Canadian Arctic Islands. Fundamental differences in basin architecture and depositional settings north and south of the Liard Line apparently have no manifestation on the sediment provenance of Yukon and WCSB strata. Therefore, we interpret the limited proportion of early Paleozoic and Neoproterozoic detrital zircons in post-Late Devonian strata of the Northwest Laurentian reference frame (e.g., Ross et al. 1997; Gehrels and Ross 1998) to be an artifact of sample size and analytical technique. Provenance and fossil correlations between strata in Yukon, the WCSB, and the Canadian Arctic Islands provide compelling evidence for isotopic and geochemical homogeneity along the northwestern Laurentian margin during the Triassic (cf. Ross et al. 1997).

(4) Permian shale of the upper Mount Christie Formation type section in eastern Yukon yields Silurian (ca. 430 Ma) detrital muscovite. Large analytical errors for this sample are acknowledged; however, this age is in agreement with widespread ca. 430 Ma detrital zircons in post-Late Devonian strata of the Northwest Laurentian and Arctic reference frames. Silurian detrital muscovite may, therefore, have an ultimate source from the Ellesmerian orogenic belt.

(5) Mississippian detrital zircon and detrital muscovite ages in Triassic Jones Lake and Toad formation sandstones are not compatible with a source from Laurentian rocks. An outboard, Cordilleran terrane source is more consistent with these age signatures, most likely from Paleozoic rock units composing the Yukon–Tanana terrane (see grey bar in Fig. 9; Colpron et al. 2006). The combination of Mississippian detrital mineral ages and presence of enriched ferromagnesian trace-element signatures in Triassic strata at localities 1 and 2 provide one line of evidence that the Slide Mountain and Yukon–Tanana terranes began overriding the North American continental margin in northwestern Canada by earliest Mesozoic time (cf. Nelson et al. 2006; Colpron et al. 2007). Triassic strata that crop out in the immediate footwall to structures juxtaposing the Slide Mountain and Yukon–Tanana terranes against North American rocks in southeastern Yukon (Abbott 1977; Mortensen and Jilson 1985; Murphy et al. 2006) are highly prospective for future research and may provide more substantial evidence for terrane-derived sediment deposited along the Cordilleran margin.

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