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Detrital zircon geochronology of the western Ellesmerian clastic wedge, northwestern Canada: Insights on Arctic tectonics and the evolution of the northern Cordilleran miogeocline

Luke P. Beranek1,†, James K. Mortensen1, Larry S. Lane2, Tammy L. Allen3, Tiffani A. Fraser3, Thomas Hadlari4,§, and Willem G. Zantvoort4,#
1Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Road, Vancouver, British Columbia, V6T 1Z4, Canada
2Geological Survey of Canada, 3303-33 Street North West, Calgary, Alberta, T2L 2A7, Canada
3Yukon Geological Survey, Box 2703 (K-10), Whitehorse, Yukon, Y1A 2C6, Canada
4Northwest Territories Geology Office, 4601-B 52nd Avenue, Box 1500, Yellowknife, Northwest Territories, X1A 2R3, Canada

ABSTRACT

Detrital zircon provenance investigations of mid-Paleozoic sandstone from the western Ellesmerian clastic wedge and Cordilleran miogeocline in northern Yukon and Northwest Territories, northwestern Canada, provide critical new data on the source of foreland basin sedimentation attributed to terrane accretion and plate convergence along the ancestral Arctic margin of North America. Late Devonian and early Mississippian clastic wedge strata yield “exotic” ca. 360–390, 430–460, 530–680, and 1500–1600 Ma detrital zircon populations that are consistent with source rocks that originated near the Caledonian and Timanian orogenic belts. Specifically, the Pearya and Arctic Alaska–Chukotka terranes, the landmass of Crockerland, and Caledonian rocks in eastern Greenland are the inferred sources for exotic detrital zircons in clastic wedge strata. Progressive recycling of Ellesmerian foreland basin sediments into the continental margin environment along northwestern Laurentia is indicated by the presence of ca. 360–430 Ma and 1500–1600 Ma detrital zircons in post-tectonic, middle to late Mississippian miogeocline strata in Yukon. Provenance data from these Mississippian samples record a dramatic shift in the source of the Cordilleran miogeocline, since Caledonian and Baltic (Timanide) detrital zircon signatures are not recognized in pre–Late Devonian sedimentary rocks in western Canada. Devonian strata of the Alexander terrane and Yreka subterrane (eastern Klamath terrane) have Caledonian and Baltic detrital zircon age signatures similar to Ellesmerian clastic wedge sandstones, implying that several Cordilleran terranes originated in the paleo-Arctic realm. Speculative correlations suggest that the Arctic Alaska–Chukotka terrane was located to the west of Crockerland and the Canadian Arctic Islands in pre-Cretaceous time, prior to opening of the Amerasian basin. Rifting models for the western Arctic Ocean featuring counterclockwise rotation of the Arctic Alaska–Chukotka terrane away from the Canadian Arctic Islands may need reevaluation.

INTRODUCTION

Early to mid-Paleozoic plate convergence along the length of the ancestral Arctic margin of northern Laurentia produced a southward-tapering clastic wedge that covered ~7,000,000 km² of the North American continent, including Greenland (Fig. 1; Trettin, 1991; Patchett et al., 2004). Clastic wedge strata accumulated in the foreland of the Innuitian orogen (Fig. 1), a mountain belt characterized by growth that has been attributed to the progressive collision of allochthonous terranes against northern North America (Trettin et al., 1991; Patchett et al., 1999). The final pulse of Innuitian orogenic development and sedimentation in northern Laurentia was related to the enigmatic Late Devonian to Mississippian Ellesmerian orogeny (Thorsteinsson and Tozer, 1970; Trettin et al., 1991; Lane, 2007).

In contrast to most foreland basin successions worldwide, the detrital zircon provenance signatures of Innuitian clastic wedge strata are relatively unconstrained. Provenance analysis of foreland strata is accepted as a very useful tool in understanding orogen evolution (e.g., Ross et al., 2005). Therefore, detrital zircon age analysis of clastic wedge rocks is an excellent way to place tighter constraints on Paleozoic collisional tectonics, plate reconstructions, and stratigraphic correlations within the paleo-Arctic realm.

Prior study on the Innuitian foreland basin succession includes 71 detrital zircon ages from five samples of Ellesmerian elastic wedge sandstone (McNicoll et al., 1995; Gehrels et al., 1999). Notably, conventional isotope dilution–thermal ionization mass spectrometry (ID-TIMS) analyses of detrital zircons from the Late Devonian Nation River Formation of eastern Alaska (NR in Fig. 2) yielded six ages from 424 to 434 Ma (Gehrels et al., 1999). Sensitive high-resolution ion microprobe (SHRIMP) analyses on detrital zircon from the Middle Devonian Bird Fiord Formation (BF in Fig. 2) in the Canadian Arctic Islands also yielded a single 426 Ma grain (McNicoll et al., 1995). Silurian detrital zircons in Ellesmerian elastic wedge strata are most consistent with a source from the Caledonian orogenic belt of eastern Greenland (Fig. 1) or the Pearya terrane in the Canadian Arctic Islands (Fig. 1) because ca. 430 Ma igneous rocks are not recognized on the northern Laurentian autochthon (e.g., Gehrels et al., 1999).

Silurian to Cryogenian (ca. 430–680 Ma) detrital zircon ages are widely observed within laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) data sets from Triassic Cordilleran margin strata in Yukon (Beranek et al., 2005). Therefore, detrital zircon geochronology of the western Ellesmerian clastic wedge, northwestern Canada, provides critical new data on the source of foreland basin sedimentation attributed to terrane accretion and plate convergence along the ancestral Arctic margin of North America.
Figure 1. Generalized distribution of Innuitian clastic wedge strata, sedimentary dispersal patterns during the Devonian, and Phanerozoic mountain belts of North America (modified from Patchett et al., 1999, 2004).

Figure 2. Distribution of tectonic elements and geologic features of northern Alaska and Canada (modified from Colpron and Nelson, 2009). BF indicates the location of the Middle Devonian Bird Fiord detrital zircon sample of McNicoll et al. (1995). NR represents the Late Devonian Nation River Formation detrital zircon sample of Gehrels et al. (1999).
et al., 2010), Triassic sandstone in the Canadian Arctic Islands (Miller et al., 2006), and Paleozoic metaclastic units underlain by Ediacaran and older rocks of the Arctic Alaska–Chukotka terrane (Figs. 2 and 3) in northern Alaska (Moore et al., 2007; Amato et al., 2009). Peninsularian and Triassic Cordilleran margin strata in Alberta and British Columbia also contain ca. 430 Ma detrital zircons (ID-TIMS; Ross et al., 1997; Gehrels and Ross, 1998). The Nd isotopic signatures of Mississippian to Triassic strata of the Cordilleran miogeocline are in agreement with a source from Ellesmerian clastic wedge units, indicating that Innuitian foreland basin sediments were continuously cannibalized and recycled into younger rocks along the western Laurentian margin (Boghossian et al., 1996; Ross et al., 1997; Garzione et al., 1997; Patchett et al., 1999, 2004; Beranek et al., 2010).

Although it is generally accepted that the Innuitian hinterland terranes originated near the Tintanian orogenic belt of Baltica and the Caledonides of northern Europe and Greenland (e.g., Trettin, 1987; Amato et al., 2009), the early to mid-Paleozoic paleogeography and configuration of these tectonic elements are not well understood (Lawver et al., 2002). This problem is exacerbated by the dismemberment of the Innuitian hinterland during late Mesozoic opening of the Arctic Ocean and formation of the Eurasian and Amerasian basins (e.g., Miller et al., 2006). One tectonic argument of considerable debate features the “rotational opening model,” in which Cretaceous rifting rotated the Arctic Alaska–Chukotka terrane away from the Canadian Arctic Islands about a pole in the Mackenzie River delta region (e.g., Lawver and Scotese, 1990; Lane, 1997; Lawver et al., 2002; Toro et al., 2004; Miller et al., 2006). Crustal extension associated with Amerasian basin formation also led to the fragmentation and foundering of continental crust, and Embry (1992) referred to one such submerged landmass as “Crockerland.” The now-missing Crockerland, perhaps once 250,000 km² in size, is presently overlain by Neoproterozoic to early Paleozoic volcanic and marine sedimentary rocks (Trettin, 1991). The Pearya terrane also records a Middle Ordovician deformational event compatible in age to the Taconic orogeny in the northern Appalachians (Trettin et al., 1991). Late Silurian convergence led to the formation of the Clements Markham fold-and-thrust belt and basement-cored Boothia Uplift in the Canadian Arctic Islands (Fig. 2). The timing of Pearya terrane accretion is similar to that of the Scandian phase of the Caledonian orogen, in which the continent-continent collision between Baltica and Laurentia was driven by closure of the Iapetus Ocean (Stephens and Gee, 1985; Trettin, 1991). The Pearya terrane also records a Middle Ordovician deformational event comparable in age to the Taconic orogeny in the northern Appalachians (Trettin et al., 1991). The Pearya terrane is composed of pre-Mesoproterozoic metasedimentary and metavolcanic rocks intruded by 1000–1100 Ma plutons (U-Pb ID-TIMS; Trettin et al., 1987) and overlain by Neoproterozoic to early Paleozoic volcanic and marine sedimentary rocks (Trettin, 1987). Neoproterozoic sedimentary units on northern Ellesmere Island (Fig. 2) are similar to coeval assemblages in southwestern Spitsbergen.

**GEOLOGIC FRAMEWORK**

The detrital zircon signature of Ellesmerian clastic wedge strata is genetically linked to source rocks involved in Innuitian orogenesis. Discrete phases of deformation, magmatism, and sedimentation in the paleo-Arctic realm are outlined next to describe the regional geologic framework and detrital zircon source areas.

**Late Silurian**

The Late Silurian accretion of the Pearya terrane against the ancestral Arctic margin of Laurentia by sinistral transpression was the earliest phase of Innuitian orogenesis (Trettin et al., 1991). Late Silurian convergence led to the formation of the Clements Markham fold-and-thrust belt and basement-cored Boothia Uplift in the Canadian Arctic Islands (Fig. 2). The timing of Pearya terrane accretion is similar to that of the Scandian phase of the Caledonian orogen, in which the continent-continent collision between Baltica and Laurentia was driven by closure of the Iapetus Ocean (Stephens and Gee, 1985; Trettin, 1991). The Pearya terrane also records a Middle Ordovician deformational event comparable in age to the Taconic orogeny in the northern Appalachians (Trettin et al., 1991). The Pearya terrane is composed of pre-Mesoproterozoic metasedimentary and metavolcanic rocks intruded by 1000–1100 Ma plutons (U-Pb ID-TIMS; Trettin et al., 1987) and overlain by Neoproterozoic to early Paleozoic volcanic and marine sedimentary rocks (Trettin, 1987). Neoproterozoic sedimentary units on northern Ellesmere Island (Fig. 2) are similar to coeval assemblages in southwestern Spitsbergen.
Early to Middle Devonian

The Arctic Alaska–Chukotka terrane is a large (3,000,000 km²) crustal fragment that underlies the North Slope and Seward Peninsula of northern Alaska and the Chukotka Peninsula and Bering and Siberian continental shelves along northeastern Russia (Amato et al., 2009). Felsic metavolcanic and meta- plutonic rocks of the terrane yield U-Pb zircon ages by ID-TIMS and SHRIMP methods of 540–565, 650–710, 870, and 971 Ma, which are similar in age to magmatic events documented in Svalbard, the E diacanar Timanide orogenic belt of Bafica, and peri-Gondwanan Avalonian-Cadomian arc systems (e.g., Patric and McClelland, 1995; Gee and Pease, 2004; Amato et al., 2009). The southern margin (present coordinates) of the Arctic Alaska–Chukotka terrane (Coldfoot and Hammond subterrains in Fig. 2) was the site of Middle Devonian (ca. 375–390 Ma), and pos- sibly Early Devonian (405 Ma), arc magma- tism of the Ambler sequence (U-Pb SHRIMP; McClelland et al., 2006; Rateman et al., 2006). Middle Devonian (ca. 390 Ma) metaplutonic rocks are also recognized on the Seward Penin- sula (Till et al., 2006; Amato et al., 2009).

Field, subsurface, and detrital zircon data demonstrate that early Paleozoic rocks of the Arctic Alaska–Chukotka terrane were affected by intense regional deformation in the Innui- tian realm after Late Silurian accretion of the Pearya terrane. In the eastern Arctic Alaska–Chukotka terrane, isoclinal folding and north- directed thrust faulting developed during the late Early Devonian to earliest Middle De- vonian (ca. 395 Ma) Romanzof orogeny (Fig. 2; Lane, 2007). Romanzof orogeny records an Early to Middle Devonian phase of deforma- tion related to the progressive accretion of a continent-scale terrane against the northwestern Laurentian margin (Lane, 2007). Romanzovz structures in northern Yukon are crosscut by Late Devonian (ca. 360–375 Ma) plutons (U-Pb ID-TIMS; Mortensen and Bell, 1991; Lane, 2007).

Mississippian conglomerate above a sub- Mississippian unconformity in the northeastern Brooks Range contains 320–390, 560–900, and 1200–1450 Ma detrital zircons that are not observed in a sample of the underlying Neoprotero- zoic quartzite (SHRIMP and LA-ICP-MS; Moore et al., 2007). The provenance signatures of the Mississippian conglomerate are also different to those of Silurian to Mississippian rocks in the western Arctic Alaska–Chukotka terrane, which yield 390–440, 475–600, and 1500–1700 Ma detrital zircons (Moore et al., 2007; Amato et al., 2009). Moore et al. (2007) interpreted the Mississippian conglomerate as having been deposited after regional tectonism and concluded that its detrital zircons were derived from a source region outside of the Brooks Range. Detrital zircon results from several samples in the northeastern Brooks Range are comparable to those of autochthonous North American strata in east-central Alaska, indicating that the eastern Arctic Alaska–Chukotka terrane was sutured against northern Laurentia in the Devonian (Moore et al., 2007; cf. Dumoulin et al., 2000; Lane, 2007).

Late Devonian to Mississippian

The Ellesmerian orogeny in its classic sense is restricted to Late Devonian to early Mississip- pian regional deformation in the Canadian Arctic Islands and northern Greenland (e.g., Trettin et al., 1991). Ellesmerian orogeny produced a wide (>375 km) foreland fold belt and ca. 360–365 granitic intrusions (U-Pb ID-TIMS; Trettin, 1991). The cause of Late Devonian to early Mississippian deformation in the Canadian Arctic Islands remains enigmatic (e.g., Lawver et al., 2002); however, Embry (1992) suggested that the accretion of Crocker- land against northern Laurentia was responsible for Ellesmerian orogeny. The Canadian Arctic Islands, field and seismic-reflection data indicate that south- to southeast-vergent thrust faults and folds in the Mackenzie River delta and Richardson Mountains areas of northern Yukon are of Ellesmerian age (Lane, 2007, and references therein).

Ellesmerian orogeny produced an exten- sive clastic wedge sequence along the length of the entire Innuitian tectonic province (Trettin, 1991). In northern Yukon and Northwest Territo- ries, syntectonic clastic rocks of the Late De- vonian Imperial Formation and Late Devonian to early Mississippian Tuttle Formation originated from nearby orogenic highlands. Seismic- reflection data show that Imperial Formation rocks were folded by the late early Carbonifer- ous, suggesting that Ellesmerian tectonism in the Mackenzie River delta–Richardson Moun- tains area progressed to the south (Lane, 2007). The trace of the Ellesmerian deformation front in northern Yukon has not yet been identified along strike in eastern Alaska, near the Late De- vonian Nation River Formation detrital zircon sample (Fig. 2) of Gehrels et al. (1999).
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Each sample is reported with the presentation of detrital zircon age results (e.g., \( n = 51/64 \) indicates a total of 64 analyses yielded 51 ages that were <10% discordant).

SAMPLE LOCATION GEOLOGY AND DETRITAL ZIRCON RESULTS

Late Devonian Imperial Formation

The Frasnian to Famennian Imperial Formation consists of fine-grained sandstone and shale that crop out in the Richardson Mountains area of northern Yukon and eastern Mackenzie Mountains along the Yukon–Northwest Territories border (Figs. 3–5; Braman and Hills, 1992). Imperial Formation sandstone is typically composed of quartz, feldspar, chert, and accessory white mica. The Imperial Formation ranges in thickness from 590 to 1690 m, with the greatest accumulation in the Peel Plateau area of northwestern Northwest Territories (Gordey et al., 1991).

Four samples of Imperial Formation sandstone were selected for detrital zircon analysis to provide new constraints on the source of the Late Devonian Ellesmerian clastic wedge. Frasnian feldspathic sandstone of sample I1 was collected ~100 m above the base of the formation near the type section in the Mackenzie Mountains of the Northwest Territories (Fig. 5). Samples I2, I3, and I4 consist of Frasnian feldspathic sandstone, chert lithic sandstone, and quartz sandstone, respectively, selected from outcrops of the middle Imperial Formation exposed along the Dempster Highway in northern Yukon and Northwest Territories (Fig. 5).

Results

Turbiditic sandstone of sample I1 yielded detrital zircon age clusters (Fig. 6A) at 428–462 Ma (15%; 8 grains), 530–556 Ma (~10%; 5 grains), 640–657 Ma (~8%; 4 grains), 673–690 Ma (~8%; 4 grains), 1393–1512 Ma (13%; 7 grains), and 1570–1666 Ma (~8%; 4 grains). Overall, Silurian to Cryogenian detrital zircon ages form over 50% (26 grains) of sample I1. Detrital zircons older than 1700 Ma are rare in sample I1, even when accounting for grains with >10% discordance (only 5 of 64 analyses).

Samples I2–I4 contain Silurian and Ordovician (ca. 415–460 Ma) detrital zircons at a 7% level (Figs. 6B–6D). The cumulative probability plot of Figure 6 illustrates that samples I2–I4 generally have overlapping age spectra. These Imperial Formation sandstones have
large amounts of ca. 1800–2000 Ma detrital zircon, including 35% and 50% of the grains in samples I3 and I4, respectively. Archean (>2500 Ma) detrital zircons occur at ~11% level in samples I2–I4. Each sample of the Imperial Formation suite produced one to three detrital zircons of Middle to Late Devonian (ca. 360–395 Ma) age.

Late Devonian to Early Mississippian Tuttle Formation

The Famennian to Tournaisian Tuttle Formation is defined as a package of coarse-grained clastic rocks overlying the Imperial Formation in the Richardson Mountains and Peel Plateau regions of northern Yukon (Figs. 3–5; Fraser and Allen, 2007). The Tuttle Formation consists of chert conglomerate, very poorly sorted quartz and chert lithic sandstone, and micaceous sandstone, siltstone, and shale at its type section (Pugh, 1983). Surface and borehole studies indicate that the Tuttle Formation is up to 1420 m thick (Pugh, 1983; Gordey et al., 1991).

Pugh (1983) proposed that the lowermost occurrence of coarse-grained clastic strata conformably overlying Imperial Formation rocks represents the base of the Tuttle Formation. The transition is a facies boundary documenting a lateral and vertical grain-size boundary that is essentially diachronous. Therefore, the terms “upper Imperial Formation” and “lower Tuttle Formation” may be somewhat ambiguous, and geographic location may be more important than stratigraphic position. There is no consensus on the depositional setting for Tuttle Formation strata, as both marine and nonmarine alternatives have been suggested (Lutchman, 1977; Hills and Braman, 1978). South-directed paleocurrent indicators (load casts, flute casts, tool marks) imply that Tuttle Formation strata originated from a region to the north (Gordey et al., 1991). However, seismic-reflection data produced a spectral profile than the other Tuttle Formation samples east of the Richardson Mountains is dominated by ca. 1800–2000 Ma (45%; 33 grains) detrital zircons and also contains subordinate amounts of ca. 1100–1200 Ma (8%; 6 grains), 1500–1639 Ma (~7%; 5 grains), and ca. 2600–2800 Ma (~11%; 8 grains) ages (Fig. 7D).

Four detrital zircons in sample T4 gave Middle Devonian (ca. 370–397 Ma) detrital zircon were observed in both samples T1 and T2.

Latest Silurian to Ordovician (ca. 415–475 Ma) detrital zircons in sample T3 are observed at a 20% level (12 grains), which culminate in an age cluster from 431 to 438 Ma (Fig. 7C). Proterozoic age groupings are identified in sample T3 at ca. 1000–1300 Ma (15%), ca. 1400–1600 Ma (8%; 5 grains), and ca. 1800–2000 Ma (36%; 21 grains).

Quartz pebble conglomerate of sample T4 is dominated by ca. 1800–2000 Ma (45%; 33 grains) detrital zircons and also contains subordinate amounts of ca. 1100–1200 Ma (8%; 6 grains), 1500–1639 Ma (~7%; 5 grains), and ca. 2600–2800 Ma (~11%; 8 grains) ages (Fig. 7D). Four detrital zircons in sample T4 gave Middle to Late Devonian (372–387 Ma) ages.

Chert lithic sandstone of sample T5 produced a grouping of ca. 1800–2000 Ma detrital zircons at a 30% level (19 grains). Mesoproterozoic ages at ca. 1000–1300 Ma (24%; 15 grains) and ca. 1500–1650 Ma (11%; 7 grains) give sample T5 a slightly different spectral profile than the other Tuttle Formation samples east of the Richardson Mountains (see Fig. 7E and cumulative probability plot). Sample T5 yielded scattered early Paleozoic to Ediacaran (ca. 387–560 Ma) ages, including a cluster of three grains at ca. 365 Ma.

Figure 5. Distribution of Devonian and Mississippian strata and location of detrital zircon samples in the northern Richardson Mountains–Peel Plateau area of northern Yukon and Northwest Territories (NWT).
Late Devonian to Middle Mississippian Cordilleran Margin Strata

Regional extension along the northern Cordilleran margin during the Devonian led to the deposition of turbiditic clastic rocks assigned to the Earn Group (Gordey et al., 1991). The mid-Famennian to Tournaisian (?) Prevost Formation (>900 m thick) of the upper Earn Group in eastern Yukon is composed of chert pebble conglomerate and chert lithic sandstone deposited in a submarine-fan complex (Fig. 3; Gordey and Anderson, 1993). Paleo-current and petrographic data indicate that Prevost Formation rocks were derived from uplifted blocks of Late Proterozoic to early Paleozoic sandstone and chert to the northeast (Gordey et al., 1991; Gordey and Anderson, 1993). Coarse-grained chert lithic sandstone from the Prevost Formation in eastern Yukon was collected to evaluate the detrital zircon provenance signature of upper Earn Group rocks (Fig. 4).

Mississippian strata in central and eastern Yukon record stable clastic shelf sedimentation along the Cordilleran margin in the time following the deposition of Earn Group rocks and Ellesmerian orogenesis (Fig. 3; Gordey and Anderson, 1993). A single sample of middle to late Mississippian quartz sandstone from Keno Hill Quartzite was collected along the Dempster Highway in the Ogilvie Mountains of west-central Yukon (Fig. 4). Two samples of middle to late Mississippian quartz sandstone from the uppermost Tsichu formation (informal; Gordey and Anderson, 1993) were selected from adjacent outcrops in the Selwyn Mountains of easternmost Yukon (Fig. 4).

Results

Late Devonian Prevost Formation sandstone from eastern Yukon primarily yields ca. 1750–2100 Ma detrital zircon ages (68%; 51 grains), and Archean groupings at ca. 2500–2600 Ma (~11%; 8 grains) and ca. 2700–2800 Ma (9%; 7 grains) form subordinate age clusters (Fig. 8A). The youngest detrital zircon ages in this sample were at 1043, 1169, and 1355 Ma.

The sample of Mississippian Keno Hill Quartzite from west-central Yukon has discernible age groupings at 430–473 Ma (11%; 9 grains), 1000–1160 Ma (18%; 11 grains), 1503–1648 Ma (16%; 10 grains), and 1801–1867 Ma (15%; 9 grains) (Fig. 8B). Three ca. 900 Ma detrital zircons represent 5% of the sample.

Nearly 40% of sample TS1 sandstone (16 grains) is composed of Silurian to Ediacaran detrital zircons, including a cluster from ca. 425 to 435 Ma (21%; 9 grains) (Fig. 8C). Minor (~10%) age occurrences from 367 to 380 Ma and ca. 1000 to 1060 Ma are also present. Sample TS2 has large age groupings at 406–428 Ma (~18%; 10 grains), 1436–1643 Ma (~18%; 10 grains), and ca. 1800–2000 Ma (16%; 9 grains) (Fig. 8D). Populations from ca. 1000 to 1034 Ma and ca. 2600 to 2700 Ma constitute 7% of the ages in sample TS2.

Discussion

Detrital zircon results from sandstone samples in Yukon and Northwest Territories provide new geologic constraints on Ellesmerian clastic wedge and northern Cordilleran margin strata. These data are used to evaluate: (1) the source of Imperial and Tuttle Formation rocks; (2) the composition of the northern Cordilleran migrocline following Ellesmerian orogenesis; (3) the mid-Paleozoic paleogeography of Caledonian and Baltican tectonic elements in the Imm unicorn realm; and (4) implications for Cretaceous tectonic reconstructions in the circum-Arctic region. Provenance correlations are made by comparing data from this study with those of prior detrital zircon investigations in western and northern North America (see Fig. 9).

Source of Ellesmerian Clastic Wedge Strata

Imperial Formation

The composite Late Devonian Imperial Formation detrital zircon data set (n = 192; Fig. 9A) yields significant age peak populations (>10 grains) at 428, 434, 442, 1158, 1405, 1697, 1824, 1966, 2058, 2098, and 2573 Ma. Minor (>5 grains) populations are recognized at 383, 393, 551, and ca. 670–690 Ma.

Devonian (383, 393 Ma) probability peaks in Imperial Formation sandstones roughly overlap in age with the 390 ± 10 Ma pluton emplaced into the Ptearya terrane (Trettin et al., 1987) and igneous rocks in the western and southern Arctic Alaska–Chukotka terrane (McClelland et al., 2006; Amato et al., 2009). Silurian to Ordovician age peaks (428–442 Ma) correlate with the main phase of Caledonian magmatism in eastern Greenland (e.g., Watt et al., 2000; see shaded gray bar in Fig. 9) and the 424–343 Ma detrital zircon occurrences in Middle to Late Devonian clastic wedge strata in the Canadian Arctic Islands (Fig. 9G; McNicoll et al., 1995) and eastern Alaska (Fig. 9H; Gehrels et al., 1999). Ediacaran to Cryogenian (ca. 550–680 Ma) ages, which were only observed in sample 11, suggest provenance linkages with the Arctic Alaska–Chukotka terrane (Fig. 9L; Amato et al., 2009; see shaded gray bar in Fig. 9 and later discussion). Paleoproterozoic (ca. 1800–2000 Ma) detrital zircons in the Imperial Formation are comparable in age to crystalline rocks of the northwest Laurentian craton (e.g., Hoffman, 1988; see shaded gray bar in Fig. 9) and detrital zircon occurrences in pre–Late Devonian Cordilleran margin strata in western Canada.
Paleozoic populations (>5 grains) also occur at 371, 381, 446, and 462 Ma.

Early to Late Devonian detrital zircon ages in the Tuttle Formation samples are consistent with a source from ca. 360–390 Ma intrusive rocks emplaced into the Arctic Alaska–Chukotka terrane (McClelland et al., 2006; Lane, 2007; Amato et al., 2009), and the Pearya terrane in the Canadian Arctic Islands (Trettin et al., 1987). Silurian to Ordovician detrital zircons overlap in age with new results from the Imperial Formation (Fig. 9A), Middle to Late Devonian clastic wedge strata in the Canadian Arctic Islands (Fig. 9G; McNicoll et al., 1995) and eastern Alaska (Fig. 9H; Gehrels et al., 1999), and Caledonian magmatism in eastern Greenland (see shaded gray bar in Fig. 9). Mesoproterozoic (ca. 1000–1300 Ma) ages, which are more prevalent in the Tuttle Formation than in the Imperial Formation, correspond to detrital zircon occurrences in Ordovician to Devonian strata along the Cordilleran margin (Figs. 9E and 9F; Gehrels and Ross, 1998; Gehrels et al., 1999) and the Canadian Arctic Islands (Fig. 9G; McNicoll et al., 1995). These ca. 1000–1300 Ma “Grenville-age” detrital zircons have many possible sources in the paleo-Arctic realm, including the Pearya terrane and rocks of similar affinity in Greenland and the western Baltic Shield (e.g., Trettin et al., 1987; Åhäll and Connelly, 1998) or North American strata derived from the Grenville Province of eastern Laurentia (e.g., Rainbird et al., 1992).

Early Mesoproterozoic to late Paleoproterozoic (1500–1630 Ma) detrital zircons, i.e., 13 grains with probability age peaks at 1502 and 1622 Ma, are not typical of northern Laurentian rocks but generally correspond to the 1490–1610 Ma North American magmatic gap (Van Schmus et al., 1993; see shaded gray bar in Fig. 9). Although 1430–1500 Ma anorogenic igneous rocks in the eastern Laurentian craton overlap with this magmatic gap (e.g., Ross and Villeneuve, 2003), results from the Tuttle Formation also correlate in age with rocks in northern Europe involved in Caledonian orogenesis, such as the 1502 ± 3 Ma gabbro-granite complexes of southwestern Sweden (ID-TIMS; Åhäll and Connelly, 1998). Detrital zircon ages from ca. 1500 to 1625 Ma are also recognized in Proterozoic metasedimentary rocks of Svalbard (ID-TIMS; Balashov et al., 1996; Hellman et al., 1997) and southwestern Sweden (SHRIMP; Knudsen et al., 1997; Åhäll et al., 1998). Similarly, Paleozoic metasedimentary rocks of the Arctic Alaska–Chukotka terrane in northwestern Alaska have detrital zircon probability age peaks at 1495 and 1613 Ma (Fig. 9L, see later discussion; Amato et al., 2009). Paleoproterozoic (ca. 1800–2000 Ma) and Archean (ca. 2600 Ma) ages in the Tuttle Formation are comparable to those of the Imperial Formation (Fig. 9A), pre-Late Devonian strata in western Canada and eastern Alaska (Figs. 9D–9F; Gehrels and Ross, 1998; Gehrels et al., 1999), and Middle to Late Devonian Ellesmerian clastic wedge rocks (Figs. 9G and 9H; McNicoll et al., 1995; Gehrels et al., 1999).

The occurrences of Devonian, Silurian to Ordovician, and early Mesoproterozoic to late Paleoproterozoic detrital zircons indicate that Tuttle Formation strata were in part derived from Innuitian terrane and Caledonian rocks, in agreement with the source regions to the north-northeast determined by paleocurrent and seismic-reflection data (Gordey et al., 1991; Hadlari et al., 2009). The Tuttle Formation samples contain more Devonian (ca. 360–390 Ma) and Mesoproterozoic and late Paleoproterozoic (ca. 1000–1300, 1500–1610 Ma) detrital zircons, and lesser amounts of Silurian to Cryogenian (ca. 430–680 Ma) ages, than those of the Imperial Formation suite. We speculate that this provenance shift may be attributed to the progressive unroofing and erosion of Innuitian crustal blocks during Ellesmerian orogenesis. For example, feldspathic sandstone of the Imperial Formation suite contains Silurian to Ediacaran detrital zircon likely from high level volcanic and plutonic rocks, while Devonian and Mesoproterozoic grains in the quartzose

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Figure 7. Relative probability and cumulative probability plots (0–3000 Ma and 300–700 Ma) displaying detrital zircon ages from the Tuttle Formation: (A) sample T1—lower Tuttle Formation quartz sandstone; (B) sample T2—lower Tuttle Formation quartz sandstone; (C) sample T3—upper Tuttle Formation quartz sandstone; (D) sample T4—quartz pebble conglomerate; and (E) sample T5—lower Tuttle Formation chert lithic sandstone.
Late Devonian to Triassic Evolution of the Northern Cordilleran Miogeocline

Prevost Formation sandstone from eastern Yukon yields detrital zircon age peaks at 1755, 1826, 1896, and 2000 Ma that correlate with prior analyses of pre-Late Devonian Cordilleran margin strata in western Canada (Figs. 9D and 9F; Gehrels and Ross, 1998) and eastern Alaska (Fig. 9E; Gehrels et al., 1999). These data suggest that upper Earn Group strata originated from uplifted blocks of Neoproterozoic to early Paleozoic Cordilleran margin rocks (cf. Gordey and Anderson, 1993).

The composite detrital zircon signature of quartzose middle to late Mississippian strata from the northern Cordilleran margin sequence (n = 158; Fig. 9C) consists of dominant (>14 grains) age peak populations at 382, 415, 431, 1033, 1139, 1499, 1702, 1783, 1824, and 1940 Ma. All of these populations are identified as ages or probability age peaks in Late Devonian to early Mississippian clastic wedge strata located in northern Yukon and Northwest Territories (Figs. 9A and 9B). Prior to these analyses on middle to late Mississippian strata, early Paleozoic detrital zircons were not observed in the Cordilleran miogeoclone until Pennsylvania-Permian time (Gehrels and Ross, 1998; see Figs. 9D and 9F).

Triassic Cordilleran margin strata in Yukon are rich in ca. 430 Ma detrital zircons and have appreciable amounts of Middle to Late Devonian, Cambrian to Cryogenian, and early Mesoproterozoic to late Paleoproterozoic ages (Fig. 9I; Beranek et al., 2010). We interpret these data, in combination with middle to late Mississippian sample results, to demonstrate that ca. 360–390, 430–680, and 1500–1600 Ma detrital zircons in clastic wedge strata were continuously cambialized and recycled into younger Cordilleran margin rocks along western Laurentia. Whole-rock Nd isotopic data from middle Mississippian to Triassic Cordilleran margin strata in western Canada also support the post-Late Devonian sedimentary recycling of clastic wedge strata (Boghossian et al., 1996; Garzione et al., 1997; Ross et al., 1997; Beranek et al., 2010; cf. Patchett et al., 1999, 2004).

Mid-Paleozoic Paleogeography of Arctic Terranes

Numerous multidisciplinary studies have placed constraints on the mid-Paleozoic paleogeography of Innuittian and Cordilleran terranes with Caledonian, Baltic, and Siberian affinities (e.g., Soja, 1994; Bazard et al., 1995; Patrick and McClelland, 1995; Gehrels et al., 1996; Dumoulin et al., 2000; Blodgett et al., 2002; Amato et al., 2009; Colpron and Nelson, 2009). Detrital zircon analysis of the western Ellesmerian clastic wedge also provides general insights on mid-Paleozoic Arctic paleogeography. The mid-Paleozoic plate reconstruction of Figure 10, modified from that of Colpron and Nelson (2009), illustrates the conclusions listed herein.

Embry (1992) suggested that the juxtaposition of Crockerland against northern Laurentia produced the Ellesmerian orogeny because a continental landmass is required as a sediment source for Carboniferous to Jurassic strata in northern Canada. The Triassic Pat Bay Formation in the Canadian Arctic Islands (Fig. 9K) and the Triassic Ivishak Formation underlain by Arctic Alaska–Chukotka terrane rocks in northern Alaska (Fig. 9J) originated from Crockerland and yield ca. 460–590, 1000–1300, 1600–1700, and 1800–1900 Ma detrital zircons, including large probability age peaks at ca. 530–590 Ma (Miller et al., 2006). Comparison with the 500–600 Ma detrital zircons in the Imperial Formation samples (Fig. 9A) implies that Crockerland supplied at least part of the Late Devonian Ellesmerian clastic wedge in northern Yukon and Northwest Territories (CL in Fig. 10).

Paleozoic metaclastic rocks of Arctic Alaska–Chukotka terrane in northwestern Alaska are dominated by ca. 400–440, 545–620, and 660–700 Ma detrital zircons (Fig. 9L; Amato et al., 2009). These metasedimentary units also exhibit detrital zircon ages correlative with the 1490–1610 Ma North American magmatic gap and have a paucity of ca. 1800–2000 Ma ages that characterize northwest Laurentian strata (Fig. 9). The detrital zircon profiles of Late Devonian to Triassic rocks in the Alaskan and northern Canadian Cordillera (Figs. 9A–9C, 9G, and 9I; Gehrels et al., 1999; Beranek et al., 2010), in particular their ca. 430 and 500–700 Ma ages, correspond well with that of the composite signature of Arctic Alaska–Chukotka terrane metaclastic rocks (Fig. 9L; Amato et al., 2009). Notably, Arctic Alaska–Chukotka terrane metaigneous rocks yield U-Pb SHRIMP and ID-TIMS age ranges of ca. 360–390, 540–565, and 650–710 Ma (e.g., Patrick and McClelland, 1995; Amato et al., 2009), in agreement with several probability age peaks in clastic wedge and miogeoclinal sample suites (Fig. 9). Overall, we infer the late Early to early Middle Devonian Romanzof orogeny allowed the Arctic Alaska–Chukotka terrane to be a source for Late Devonian to early Mississippian strata in northwestern Laurentia (AA in Fig. 10).

In their treatment of early to mid-Paleozoic Arctic paleogeography, Colpron and Nelson (2009) suggested the Okanagan subterrane of Quesnellia (OK in Fig. 10), Yureka and Trinity
Figure 9. Relative probability plots (0–3000 Ma and 200–700 Ma) for U-Pb detrital zircon data from this and prior studies. Errors from all data sets are plotted at the 2σ level. (A) Composite signature for Late Devonian Imperial Formation samples presented in Figures 6A–6D. (B) Composite signature for Late Devonian to early Mississippian Tuttle Formation samples displayed in Figures 7A–7E. (C) Composite signature for middle Mississippian samples of Figures 8B–8D. (D) Neoproterozoic to Cambrian miogeoclinal strata, British Columbia and Alberta (TIMS; Gehrels and Ross, 1998). (E) Cambrian miogeoclinal sandstone, eastern Alaska (TIMS; Gehrels et al., 1999). (F) Ordovician to Early Devonian miogeoclinal rocks, British Columbia and Alberta (TIMS; Gehrels and Ross, 1998). (G) Composite signature of Middle Devonian clastic wedge strata, Canadian Arctic Islands (SHRIMP; McNicoll et al., 1995). (H) Late Devonian Nation River Formation, eastern Alaska (TIMS; Gehrels et al., 1999). (I) Composite signature of Early to Late Triassic marine strata, western-central to southeastern Yukon (LA-ICP-MS; Beranek et al., 2010). (J) Early Triassic Ivishak Formation, North Slope of northern Alaska (LA-ICP-MS; Miller et al., 2006). (K) Late Triassic Pat Bay Formation, Canadian Arctic Islands (LA-ICP-MS; Miller et al., 2006). (L) Composite signature of Paleozoic metasedimentary rocks of the Arctic Alaska–Chukotka terrane, northwestern Alaska (LA-ICP-MS; Amato et al., 2009). (M) Composite signature of Ordovician to Triassic strata of the Alexander terrane, southeastern Alaska (TIMS; Gehrels et al., 1996). Shaded gray bars in the 0–3000 Ma plot correspond to the northward translation of the Arctic Alaska–Chukotka terrane (Van Schmus et al., 1993) and northwest Laurentian craton (Hoffman, 1988). Shaded gray bars in 200–700 Ma plot indicate Silurian–Ordovician magmatism in the Caledonides of Greenland (Watt et al., 2000) and Neoproterozoic magmatism in the Arctic Alaska–Chukotka terrane (Amato et al., 2009, and references therein).

In their model, the Okanagan terrane and Yreka and Trinity subterranes were transported westward from their origin by sinistral strike-slip motion during the Silurian, were involved in Early to Middle Devonian Romanzof deformation in northwestern Laurentia, and were then translated south alongside the Cordilleran margin of western North America. According to Colpron and Nelson (2009), the Late Devonian to early Mississippian accretion of the Yreka

subterranes of the eastern Klamath terrane (YR in Fig. 10), and Alexander terrane (AX in Figs. 4 and 10) in the North American Cordillera originated near the Caledonian and Timanian orogenic belts of present-day northern Europe.
and Trinity subterranes against the Cordilleran margin was responsible for Antler orogenesis in the western United States (Fig. 10). Early to Middle Devonian strata of the Yreka subterranes yield ca. 430 Ma and 1490–1610 Ma detrital zircons (SHRIMP and LA-ICP-MS; Grove et al., 2008), which are consistent with Caledonian and Timanide sources, the signatures of Ellesmerian clastic wedge (Figs. 9A and 9B), and northern Cordilleran miogeoclinal strata (Figs. 9C and 9F; Beranek et al., 2010). Holocene to Neogene sediments derived from rocks of the Antler allochthon and adjacent foreland basin succession in south-central Idaho yield ca. 360–460 Ma and 1500–1600 Ma detrital zircon ages (SHRIMP; Link et al., 2005; Beranek et al., 2006), which are also observed in Ellesmerian clastic wedge and Yreka subterranes data sets, further suggesting that Antler terrane rock assemblages originated near the Caledonides.

The oldest units of the Alexander terrane (AX in Fig. 4), which underlies large portions of southeastern Alaska, northwestern British Columbia, and southwestern Yukon, include Edeianaran (554–595 Ma), Middle Ordovician (ca. 460 Ma), and Silurian (ca. 430 Ma) igneous rocks (U-Pb ID-TIMS; Gehrels et al., 1987; Gehrels, 1990). Early Paleozoic detrital zircon age peaks at ca. 360, 429, 459, and 480 Ma are also ubiquitous in Ordovician to Triassic strata (Fig. 9M; TIMS; Gehrels et al., 1996). Detrital and igneous U-Pb zircon ages from Alexander terrane rocks correlate with results from the Ellesmerian clastic wedge (Figs. 9A, 9B, 9G, and 9H; McNicoll et al., 1995; Gehrels et al., 1999), Mississippiian and Triassic Cordilleran margin rocks (Figs. 9C and 9F; Beranek et al., 2010), and Arctic Alaska–Chukotka terrane metamorphic (Fig. 9L; Amato et al., 2009). Both of these Triassic samples yield ca. 360–500 Ma detrital zircons that form probability age peaks in Paleozoic metasedimentary strata of the Arctic Alaska–Chukotka terrane (Fig. 9L; Amato et al., 2009). These discrepancies suggest that late Paleozoic and Mesozoic strata of the Arctic Alaska–Chukotka terrane did not receive sediment from the Arctic Alaska–Chukotka terrane, but sediment came only from Crockerland, the Pearya terrane, eastern Greenland, and the Laurentian craton. The southern margin of the Arctic Alaska–Chukotka terrane in Figure 10, which is the present-day eastern part of the terrane, was sutured to northwestern Laurentia during the Romanzof orogeny, suggesting it lay to the west of Crockerland and the Pearya terrane. These relationships imply that the Arctic Alaska–Chukotka terrane was not located alongside the Canadian Arctic Islands from Late Devonian to Cretaceous time (Fig. 10).

CONCLUSIONS

New provenance constraints indicate that Ellesmerian clastic wedge sandstone samples from the Imperial and Tuttle Formations in northern Yukon and Northwest Territories, northwestern Canada, contain ca. 360–390, 430–460, 530–680, and 1500–1600 Ma detrital zircons derived from allochthonous terranes that originated near the Caledonian and Timanide orogenic belts of northern Europe. Regional correlations suggest that exotic detrital zircons in Imperial and Tuttle Formation strata originated from the Arctic Alaska–Chukotka terrane, Pearya terrane, the landmass of Crockerland,
Arctic Islands, which should be considered in Alaska–Chukotka terrane and the Canadian Arctic Archipelago. Signatures correlate with provenance data from the Upper Devonian to Lower Carboniferous Tullite Formation, eastern Richardson Mountains, Yukon, in Enomoto, D.S., Lewis, L.L., and Weston, L.H., eds., Yukon Exploration and Geology 2006: Whitehorse, Yukon, Geological Survey of Canada, Open File 5393.

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