Closing the Canada Basin: Detrital zircon geochronology relationships between the North Slope of Arctic Alaska and the Frankonian mobile belt of Arctic Canada

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ABSTRACT
Constraining the pre-opening paleogeography of the Canadian and Alaskan margins of the Canada Basin is a first-order objective in resolving the plate tectonic evolution of the Amerasian Basin of the Arctic Ocean. The most widely accepted model for opening of the Canada Basin involves counterclockwise rotation of Arctic Alaska away from Arctic Canada about a pole of rotation in the Mackenzie Delta region, although numerous other kinematic models have been proposed. The rotation model is tested using detrital zircon U-Pb geochronology of 12 samples from Middle Mississippian to Early-Middle Jurassic strata (Ellesmerian and lower Beaufortian megasequences) obtained from wells and outcrop along Alaska’s North Slope. These northerly-derived strata were deposited in fluvial to nearshore marine environments along the south-facing (present-day) shelf margin of the Arctic Alaska Basin and contain 360–390 Ma, 415–470 Ma, 500–750 Ma, 0.9–2.1 Ga, and 2.4–3.2 Ga zircon populations. Detrital zircon age populations in Ellesmerian and lower Beaufortian strata are remarkably similar to detrital zircon populations from Devonian foreland clastic wedge strata in the Canadian Arctic Islands and northern Yukon Territory. A paleogeographic setting in which Arctic Alaska received sediments recycled from the Devonian foreland clastic wedge and underlying Franklinian Basin strata is most consistent with the model of Embry (1990) in which northern Alaska lay within the foreland fold and thrust belt of the Franklinian mobile belt prior to the opening of the Canada Basin. The sequences that are inferred to have been the long-lived source region for Ellesmerian and lower Beaufortian strata were uplifted by Paleozoic (predominantly Late Devonian) deformation that has been documented along the Canadian and Alaskan margins. Triassic and Jurassic strata deposited along the Arctic Canada, Arctic Alaska, and northern Yukon shelves have detrital zircon ages that are significantly older than the youngest detrital zircon ages (Mesozoic) in coeval strata that were deposited west of Hanna Trough and north of the Sverdrup Basin axis, supporting continuity of these bathymetric features prior to opening of the Canada Basin.

INTRODUCTION
The Canada Basin is a first-order bathymetric feature of the Arctic Ocean, defined in part by high-relief rifted escarpments (>3 km shelf to basin) along the north Alaskan and north Canadian margins, which meet in the Mackenzie Delta region of the Beaufort Sea (Fig. 1). Establishing the paleogeographic relationship of the margins of the Canada Basin prior to rifting is essential to understanding the Mesozoic and younger plate tectonic evolution of the broader Amerasian Basin of the Arctic Ocean. The Eurasia and Amerasian basins of the Arctic Ocean are surrounded by broad continental shelves (Fig. 1A), and they are thought to be the product of at least two stages of rifting and seafloor spreading (recent summary in Dissing et al., 2013). Beginning in Paleocene time, the mid-Atlantic rift propagated northward to form the Eurasia Basin by spreading along the Gakkel Ridge (Fig. 1A) (Kristoffersen, 1990). The Lomonosov Ridge is a rifted continental fragment (Sweeney et al., 1982) that separates the Eurasia Basin from the older composite Amerasian Basin, which includes the Canada Basin (Fig. 1) (Jakobsson et al., 2012).

The most widely accepted hypothesis for the origin of the Canada Basin is that it opened in Mesozoic time by counterclockwise rotation of the north Alaskan margin away from the north Canadian margin around a pole of rotation near the Mackenzie Delta (e.g., Carey, 1958; Taillour, 1973; Vogt et al., 1982; Lawver et al., 1990; Grantz et al., 1998; Shephard et al., 2013; summary in Lawver and Scotese, 1990). In addition to bathymetric evidence that suggests these two margins may be conjugate (Fig. 1), numerous independent arguments have been put forth to support the rotation hypothesis. A linear gravity low in the Canada Basin that trends toward the suggested pole of rotation has been interpreted as an extinct spreading ridge (Grantz et al., 1979; Laxon and McAdoo, 1994). Breakup unconformities of Early Cretaceous age have been mapped on seismic and well data along each margin (Grantz and May, 1983; Embry and Dixon, 1990). Correlations of lithology, sediment transport directions, stratal geometries, and structural trends in the pre-breakup stratigraphy of both margins have been cited to support proximity of the two margins before basin opening (Grantz and May, 1983; Embry, 1990; Toro et al., 2004).

Alternative models for the origin of the Canada Basin (review by Lawver and Scotese, 1990) invoked oceanization of continental crust (e.g., Belousov, 1970), trapping of older oceanic crust (e.g., Churkin, 1970), or opening of the Canada Basin primarily by transform motion along either the Canadian margin (e.g., Johnson and Heezen, 1967) or Alaskan margin (e.g., Herron et al., 1974). These models have generally lost support with new geophysical imaging of the Arctic Ocean (e.g., McAdoo et al., 2008). However, numerous timing, kinematic, and geometric constraints along the margins have been used to argue against the rotational opening of the Canada Basin (Lane, 1997). Thus, there is no universally accepted model for birth, age, and evolution of the Canada Basin.
A broader rotational opening model for the entire Amerasia Basin (e.g., Tailleur, 1973) is more problematic in that it does not explain the closer affinity of the Russian part of the Arctic Alaska–Chukotka microplate (Fig. 1A) with Eurasia rather than Canada (e.g., Miller et al., 2006, 2010) and does not adequately explain the overlap of the Chukchi Borderland with the Canadian Arctic margin upon restoration (Grantz et al., 1979; Vogt et al., 1982). The formation of the Amerasia Basin is likely to have been kinematically more complex, involving multiple episodes of motion between microplate fragments (e.g., Shephard et al., 2013). Despite these issues, the rotational opening model may adequately explain the opening of the Canada Basin part of the Amerasia Basin.

In order to test the rotational opening hypothesis for the Canada Basin, we carried out detrital zircon geochronology of northerly-derived strata deposited along the northern margin of Arctic Alaska. We then compared these data to recently published detrital zircon data sets from Paleozoic to Mesozoic strata of the Canadian Arctic and northernmost Cordilleran margins of Laurentia (Miller et al., 2006; Beranek et al., 2010a, 2010b; Lemieux et al., 2011; Omma et al., 2011; Malone, 2012; Anfinson et al., 2012a, 2012b). Analysis of the data obtained from Mississippian to Jurassic strata deposited along the Arctic continental margin of Canada (Trettin et al., 1991; Patchett et al., 1999). However, paleoenvironment and provenance signatures based on detrital zircon studies of clastic stratigraphic intervals in the mobile belt indicate three distinctive tectonostratigraphic sequences (Anfinson et al., 2012a). (1) The Neoproterozoic to Early Silurian interval reflects passive margin deposition sourced from the Laurentian continent and deposited within the Frankilnian shelf platform, slope, and marginal basin developed along the Arctic continental margin of Canada (Trettin, 1989; Patchett et al., 1999). (2) The Early Silurian to Early Devonian interval contains the Danish River formation, a 3000-m-thick synorogenic, deep water turbidite succession, deposited rapidly in a confined deep-water trough atop the Franklinian marginal basin and sourced from both the Greenland Caledonian orogen and from terranes of Caledonian affinity such as Svalbard and Pears (see fig. 4 of Anfinson et al., 2012a; also Higgins et al., 1991; Trettin et al., 1991; Patchett et al., 1999; Dewing et al., 2008). (3) The Middle to Late Devonian interval is associated with the “Devonian clastic wedge,” a 4000-m-thick clastic interval deposited in fluvial to nearshore settings within a foreland basin developed atop the Franklinian shelf, slope, and marginal basin during the Ellesmerian orogeny (Thorsteinsson and Tozer, 1970; Embry and Klovian, 1976; Embry, 1988; Trettin et al., 1991; Lane, 2007). This last thick clastic succession was derived from Late Devonian through Jurassic clastic strata of northern Alaska. Our detrital zircon data provide new control points for establishing pre–Canada Basin paleogeography and ultimately support a rotational opening model.

**GEOLOGIC SETTING**

The Alaskan margin of the Canada Basin parallels the coastline of northern Alaska and the northeast Chukchi shelf edge to its intersection with Northwind Ridge (Fig. 1). The Canadian margin parallels the northern edge of the Canadian Arctic Islands between the Mackenzie Delta and the eastern end of the Alpha Ridge (Fig. 1A). Decades of geological and geophysical investigations of outcrop and subsurface data from these two margins of the Canada Basin have resulted in a cohesive conceptual framework for the structural and stratigraphic architecture of each margin.

**The Canadian Margin**

In Arctic Canada, late Neoproterozoic to Late Devonian age strata have been conventionally divided into the deformed Franklinian mobile belt and the undeformed Arctic platform (e.g., Trettin, 1989; Patchett et al., 1999). However, paleoenvironment and provenance signatures based on detrital zircon studies of clastic stratigraphic intervals in the mobile belt indicate three distinctive tectonostratigraphic sequences (Anfinson et al., 2012a). (1) The Neoproterozoic to Early Silurian interval reflects passive margin deposition sourced from the Laurentian continent and deposited within the Franklinian shelf platform, slope, and marginal basin developed along the Arctic continental margin of Canada (Trettin, 1989; Anfinson et al., 2012a and references therein). (2) The Early Silurian to Early Devonian interval contains the Danish River Formation, a 3000-m-thick synorogenic, deep-water turbidite succession, deposited rapidly in a confined deep-water trough atop the Franklinian marginal basin and sourced from both the Greenland Caledonian orogen and from terranes of Caledonian affinity such as Svalbard and Pear (see fig. 4 of Anfinson et al., 2012a; also Higgins et al., 1991; Trettin et al., 1991; Patchett et al., 1999; Dewing et al., 2008). (3) The Middle to Late Devonian interval is associated with the “Devonian clastic wedge,” a 4000-m-thick clastic interval deposited in fluvial to nearshore settings within a foreland basin developed atop the Franklinian shelf, slope, and marginal basin during the Ellesmerian orogeny (Thorsteinsson and Tozer, 1970; Embry and Klovian, 1976; Embry, 1988; Trettin et al., 1991; Lane, 2007). This last thick clastic succession was derived from Late Devonian through Jurassic clastic strata of northern Alaska. Our detrital zircon data provide new control points for establishing pre–Canada Basin paleogeography and ultimately support a rotational opening model.
the Ellesmerian orogen to the north, which, in addition to likely recycling deformed Franklinian basin strata, also supplied non-Laurentian affinity detritus and recycled Caledonian orogen material onto a tectonically subsiding Canadian Arctic foreland basin (Anfinson et al., 2012a, 2012b). Much of the northern (hinterland) part of the Ellesmerian orogenic belt is assumed to have been rifted away from Arctic Canada during Mesozoic time, and is referred to as “Crockerland” (Embry, 1990, 2009; Anfinson et al., 2012a, 2012b).

Several Late Devonian age (ca. 370–360 Ma) felsic to intermediate composition plutons and dikes are intruded into the deformed Franklinian passive margin sequence on Axel Heiberg Island and into the deformed deep-water turbidite sequence on northern Ellesmere Island (Trettin et al., 1992). ⁴⁰Ar/³⁹Ar cooling ages determined on hornblende (364 ± 2 Ma) and biotite (360 ± 2 Ma) demonstrate these intrusions cooled quickly after emplacement (Trettin et al., 1992). The intrusive ages overlap the depositional age of the youngest strata preserved in the Devonian clastic wedge as indicated by the youngest zircon populations (Hadlari et al., 2013). As an example, strata of the Upper Devonian Okse Bay Formation on northern Ellesmere Island contain a minor population of 365–375 Ma detrital zircons (Malone, 2012). The depositional environment of the Okse Bay Formation is interpreted as a fluvial intermontane basin within the Ellesmerian orogenic belt (Embry, 1991).

Along the Canadian Arctic margin, the Ellesmerian orogeny is associated with a widespread angular unconformity that truncates pre-Mississippian age strata (Thorsteinsson and Tozer, 1970). Farther west along the trend of the orogen, in the northern Yukon and Northwest Territories of Canada (south of the Mackenzie Delta region, Fig. 1), the uppermost strata (Tuttle Formation) of the Ellesmerian clastic wedge have been dated by palynology to be as young as Early Mississippian (Hills et al., 1984). In the Canadian Arctic, contrasts in thermal maturity of pre- and post-unconformity stratigraphic intervals suggest that in the terminal phase of Ellesmerian deformation uplift and erosion associated with formation of the angular unconformity likely removed 2.5–6 km of Devonian and possibly Early Mississippian foreland clastic wedge strata (Embry, 1991; Gentzis et al., 1996). Mid-Mississippian (Visean) and younger strata associated with the development of the Sverdrup Basin postdate and onlap this unconformity (Stephenson et al., 1987; Harrison, 1995). A small rift-related granite pluton was intruded into metasedimentary rocks of Pearlya on northern Ellesmere Island at 334.5 ± 1.5 Ma, coeval with the deposition of the earliest postunconformity strata (Trettin et al., 1992).

Deposition along the Canadian Arctic margin after the Ellesmerian orogeny and before the opening of the Canada Basin was predominantly confined to the Sverdrup Basin, which is filled with up to 13 km of Carboniferous to Paleogene age strata (Embry and Beauchamp, 2008). The axis of the Sverdrup Basin roughly parallels the Canadian margin in the eastern Canadian Arctic Islands but turns northward and is truncated by the Canada Basin margin near Prince Patrick Island (Fig. 1A). Farther west along the Canadian margin, there was a hiatus in deposition from Late Devonian to Middle Jurassic time, which ended with the development of the margin-parallel Banks Basin, a rift basin in the center of Banks Island (Fig. 1A). The Banks Basin contains fault-bounded Late Jurassic to earliest Cretaceous age strata that are unconformably overlain by more widespread Late Cretaceous age strata (Miall, 1979). Well data indicate that Late Jurassic to Cretaceous age strata were deposited on Devonian foreland clastic wedge strata in eastern Banks Island and on Paleozoic to Neoproterozoic Franklinian Basin strata in western Banks Island (Miall, 1976).

Cratonward of the Sverdrup and Banks Basins, Mesozoic and younger strata are absent, and Devonian foreland clastic wedge or Franklinian Basin strata are exposed at the surface. Seaward of the Sverdrup and Banks Basins, all older rocks are covered by Cenozoic strata of the Arctic Coastal Plain (Miall, 1976). Embry and Dixon (1990) describe a breakup unconformity (Falvey, 1974) in several locations along the Canadian margin that ranges in age from late Albian to Cenomanian and correlates to a decrease in tectonic subsidence rate. In conjunction with the subsidence data, the progressive deposition of Upper Jurassic to lowermost Cretaceous strata in local grabens, followed by development of a major unconformity overlain by Albian and younger strata is cited as evidence of the transition from continental rifting to seafloor spreading in the Canada Basin (Embry and Dixon, 1990).

**The Alaskan Margin**

Northern Alaska experienced numerous deformational episodes during Phanerozoic time, resulting in complex structural and stratigraphic relationships (Fig. 2). The geologic history of northern Alaska (e.g., reviews by Hubbard et al., 1987; Grantz et al., 1994; Moore et al., 1994) can be divided into four tectonostratigraphic phases corresponding to the Franklinian, Ellesmerian, Beaufortian, and Brookian megasequences. To minimize confusion over historical nomenclature, it is worth noting that the Franklinian megasequence in Alaska as initially defined by Lerand (1973) was correlated to strata of the Franklinian Basin in the Canadian Arctic Islands, but time-stratigraphic correlations are problematic (e.g., Handschy, 1998). Whereas Late Devonian age strata of the foreland clastic wedge in Canada are Franklinian by definition, Middle Devonian strata are the youngest Franklinian strata in northern Alaska (Grantz et al., 1994; Lane, 2007). Deformation of the Franklinian megasequences in Canada and Alaska (during the Ellesmerian orogeny) distinguishes these strata from Ellesmerian megasequence strata that unconformably overlie Franklinian strata (Grantz et al., 1994) (Fig. 3). Thus, Late Devonian age strata of the Ellesmerian megasequence in Alaska are partially coeval with uppermost Franklinian strata of the foreland clastic wedge in Canada (Grantz et al., 1994; Moore et al., 1994; Handschy, 1998).

In northern Alaska, the Franklinian megasequence includes Proterozoic to Middle Devonian age siliciclastic, volcanic, and carbonate strata that are intruded by Devonian age granitic plutons (Dillon et al., 1980; Moore, 1987; Macdonald et al., 2009; Strauss et al., 2013) (Fig. 3). Two Devonian orogenic events have deformed Franklinian megasequence strata in northern Alaska (Grantz et al., 1994; Moore et al., 1994; Lane 2007). In the northeast Brooks Range (Fig. 2) and the Mackenzie Delta region, an early phase of deformation resulting in the folding, faulting, and weak metamorphism of Franklinian strata as young as Early Devonian is defined as the Romanzof orogeny by Lane (2007) but had previously been regarded as an early phase of the Ellesmerian orogeny by Grantz et al. (1994). Early to Middle Devonian age turbidite strata that locally unconformably overlie Early Devonian and older age strata bracket the age of the end of the Romanzof (or early Ellesmerian) orogeny to Early Devonian time. These “early Franklinian” turbidite sequences are also tightly folded and thrust faulted but unmetamorphosed, and they are unconformably overlain by undeformed Mississippian and younger strata (Lane et al., 1995). Paleozoic deformation in Alaska that involved “late Franklinian” and older strata is defined as the Ellesmerian orogeny by Lane (2007) or late Ellesmerian orogeny by Grantz et al. (1994).

The upper bound of Alaska’s Franklinian megasequence in most parts of northern Alaska is an angular unconformity (termed the pre-Mississippian unconformity) associated with the Devonian Romanzof and Ellesmerian orogenies (Moore et al., 1994; Kelley, 1999; Lane, 2007). The pre-Mississippian unconformity is widely

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exposed in the northeastern Brooks Range and has been mapped in the subsurface across most of the Arctic Coastal Plain (Kelley, 1999) and in structural windows in the central and western Brooks Range (Mull et al., 1987; Mayfield et al., 1988) (Fig. 2). However, strata deposited on the deformed Franklinian megasequence are speculated to be older than Mississippian to the west in the Hanna Trough and to the south in the Arctic Alaska Basin (terminology of Sherwood et al., 2002), where Mississippian age strata thicken significantly and locally unconformably overlie unmetamorphosed Middle to Late Devonian clastic rocks as old as Eifelian (Reiser et al., 1980; Anderson, 1991; Anderson et al., 1994; Kelley, 1999) (Fig. 2).

The Ellesmerian megasequence consists of generally southward-prograding and northward-onlapping Late Devonian through Triassic age clastic and carbonate strata, although in northern Alaska the oldest Ellesmerian strata are Mississippian in age because the Barrow Arch was an emergent structural feature during Late Devonian and Early Mississippian time (Fig. 3) (Bird, 1988; Kirschner and Rycerski, 1988). Regionally, the age of the basal strata of the Ellesmerian megasequence decreases from south to north through progressive onlap. Late Devonian Ellesmerian strata within the Brooks Range (e.g., Kanayut Conglomerate, Noatak Sandstone, and Hunt Fork Shale) prograded southwestward and were deposited in a south-erly depositional basin that developed coeval with uplift and denudation of Franklinian strata farther north in the northeast Brooks Range, North Slope, and Arctic Coastal Plain (Moore et al., 1994).

The subsidence history, systematic facies transitions, and the minor presence of volcanic and volcaniclastic strata in the Ellesmerian megasequence above the pre-Mississippian unconformity document rifting and thermal subsidence of a south-facing passive continental margin that bordered the newly formed Angayucham Ocean (Anderson et al., 1994; Moore et al., 1994; Sherwood et al., 2002). In northern Alaska east of the Hanna Trough, the Ellesmerian megasequence consists of conti-

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**Figure 2.** Detrital zircon geochronology sample localities showing samples from this study together with previously published samples. Previously published: 1—Miller et al. (2006); 2—Miller et al. (2010); 3—Macdonald et al. (2009); 4—Strauss et al. (2013). Outcrop samples from northeastern Brooks Range (NE BR): SR—Sadlerochit Mountains; WB—western British Mountains; EB—eastern British Mountains. National Petroleum Reserve-Alaska (NPRA) well samples: IN—Inigok #1; IK—Ikpikpuk #1; ES—East Simpson #1; PR—Peard #1. Symbol color scheme carried over in Figures 3 and 5. Base map and Brookian structures from Bird (2001). Pluton locations from Lane (2007) and Bird et al. (1978). Hanna Trough axis is from Sherwood et al. (2002). Pre-Late Devonian thrust in Chukchi Sea east of Hanna Trough from Kumar et al. (2011). Trace of northern limit of suspected Middle-Late Devonian “early Ellesmerian” strata from Kelley (1999). For location, see Figure 1A.
Figure 3. Generalized time stratigraphic section of Arctic Alaska Basin (modified from Bird, 2001) annotated with sampling intervals (well samples shown by circles, outcrops by squares), stratigraphic nomenclature, and major unconformities. LCU—Lower Cretaceous Unconformity; PPU—pre-Permian unconformity; PMU—pre-Mississippian unconformity; AK—Alaska. Time-stratigraphic relationships in column are drawn with reference to proximal (north) versus distal (south) portions of the basin. Symbols color coded to sampling locations in Figure 2 and age results in Figure 5. Relative distance of each sample from most northerly onlap edge is indicated by x-position of sample symbols on stratigraphic section. Timing of deposition of Canadian strata discussed in text shown on right.

We examine three competing models that specify the pre-Cretaceous paleogeographic relationship between the Canadian and Alaskan margins in sufficient detail to be tested (Fig. 4; Embry, 1990; Lane, 2007; Grantz et al., 2011). The proposed reconstructions of northern Alaska are georeferenced on a base map that includes key stratigraphic and structural elements useful for evaluating the individual reconstructions along with the relative locations of samples discussed in this paper (Fig. 4). A fundamental difference in the models is the restored location of the Alaskan margin and our sample locations with respect to exposures of Middle and Late Devonian foreland clastic wedge strata of the Canadian margin that were deformed during the Devonian to Carboniferous Ellesmerian orogeny (e.g., Trettin et al., 1991) (Fig. 4). Lane’s (2007) model invokes the presence of continent-scale accreted terrane(s) between our sample locations and the Canadian margin, whereas Embry’s (1990) model places the Alaska sample locations in close proximity to the deformed foreland clastic wedge strata (Fig. 4). The Grantz et al. (2011) model places northern Alaska in an intermediate position ca. 195 Ma but overlaps the northeastern Brooks Range with the Anderson Plain of Canada’s
Northwest Territories, and thus the model defies the conventions of rigid plate reconstruction (Fig. 4). The ~40° angle between the Alaska and Canada margins in the Grantz et al. (2011) model is also characteristic of Late Devonian (370 Ma) to Early Carboniferous (340 Ma) reconstructions in Cocks and Torsvik’s (2011) review of the Paleozoic paleogeography of Laurentia and western Laurussia, and therefore these models are considered analogous for our testing methods described herein.

Ellesmerian and lower Beaufortian strata penetrated by wells in the subsurface of the National Petroleum Reserve–Alaska (NPRAlaska) and exposed in outcrop in the northeastern Brooks Range (Figs. 2 and 3) are key sampling targets to better understand the northern source region of Ellesmerian megasequence sedimentation in Alaska. If the Alaskan and Canadian margins of the basin were joined before the Cretaceous rift opening of the Canada Basin, northerly-derived strata in Alaska could have been sourced from the Canadian margin. Likewise, during the timeframe in which the pre-Mississippian unconformity was being cut into the Franklinian megasequence in northern Alaska, northerly-derived (from a Canadian reference frame) strata deposited in the adjacent western Canadian Arctic Islands could have been sourced from Frankinlian strata of the Arctic Alaska margin. Beranek et al. (2010a) and Anfinson et al. (2012a, 2012b) have argued that the presence of non-Laurentian affinity zircon populations in the northerly-sourced Devonian clastic wedge of northern Yukon and the Canadian Arctic Islands may have been derived from “Crockerland,” a composite terrane that could have included today’s Alaskan margin of the Canada Basin (Fig. 4).

METHODS

Single-grain U-Pb geochronology of detrital zircon populations in sedimentary rocks is now a well-known and robust approach for characterizing and comparing the provenance of clastic sedimentary rocks (e.g., Gehrels, 2012). Previous detrital zircon–based investigations of the circumpolar region have yielded unique data sets for evaluating signatures and the longevity of source terranes (e.g., Rainbird et al., 1992; Gehrels et al., 1999; Miller et al., 2006, 2010, 2013; Macdonald et al., 2009; Beranek et al., 2010a, 2010b; Omma et al., 2011; Anfinson et al., 2012a, 2012b; Malone, 2012; Strauss et al., 2013). Compared to other locales within the Arctic realm, northern Alaska has received relatively little attention with regard to detrital zircon–based paleoogeographic studies, despite the well-constrained depositional history of Ellesmerian and younger stratigraphic sequences (e.g., Hubbard et al., 1987; Moore et al., 1994; Bird, 2001).

In this study, we analyze the detrital zircon populations from 12 samples of strata from the Ellesmerian and Beaufortian megasequences of the Alaskan Arctic margin to gain insight into the provenance of these strata and how it changed through time and along strike (Figs. 2 and 3; Table 1). Eight of the samples analyzed were obtained from intervals of conventional core drilled in NPRAlaska between 1978 and 1980 from strata that range in age from Mississippian to Middle Jurassic (Figs. 2 and 3; Table 1). Four of these samples are Triassic. Four additional Triassic samples were analyzed from outcrops in the northeastern Brooks Range, Alaska, and Yukon Territory, collected by Mull between

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RESULTS

U-Pb ages of detrital zircon suites from individual samples are compiled in the Supplemental Table and displayed as normalized and cumulative probability plots (Fig. 5) (Gehrels, 2010a, 2010b). Descriptions of the size, shape, and age distribution of detrital zircon populations are included in Appendix C. Individually and as a whole, the detrital zircon results are noteworthy on several fronts. For all samples, reliable ages younger than ca. 350 Ma were not present, despite the fact that nine of 12 samples are Mesozoic in age (a few anomalously young results were discarded when the data were evaluated and filtered for unreliable results, see Appendix A). Age population clusters span characteristic intervals of time, namely 360–390 Ma, 415–470 Ma, 500–750 Ma, 0.9–2.1 Ga, and 2.4–3.2 Ga, and these age populations are present in nearly all samples. The percentage of <750 Ma zircons in each sample generally decreases with younger stratigraphic ages, ranging from ~50% in the oldest sample to <10% in the youngest sample. A subtle increase in the percentage of 1.8–2.0 Ga age results is noticeable in the youngest two stratigraphic intervals sampled.

The samples analyzed are representative of a range of fluvial and marine depositional environments including proximal and distal portions of fan delta systems and clastic-rich intervals in marine shelf and carbonate platform settings (Fig. 3). The detrital zircon populations of these strata are generally similar through time, with the greatest dissimilarity represented by the contrast between the Mississippian Endicott Group and the Pennsylvanian Lisburne Group (Fig. 5). The Late Permian to Early Triassic Sadlerochit Group and younger strata generally display the same broad distribution of age populations seen in Pennsylvanian Lisburne Group strata (Fig. 5). Age results from the Early Triassic Ivishak Formation of the Sadlerochit Group display the most sample-to-sample heterogeneity, in contrast to sample populations from below and above the Ivishak Formation that are for the most part statistically indistinguishable from one another.

Additionally, given the broad similarity of all of the detrital zircon data from Triassic strata analyzed in this study, we recognize that results from sample 96DH102 (Lower Triassic Ledge Member of the Ivishak Formation) published by Miller et al. (2006) contrast remarkably with our new data set. The outcrop from which sample 96DH102 was originally collected was recently re-sampled and analyzed by Thomas Moore, yielding results that are similar to our northeast Brooks Range samples and dissimilar to what was originally reported as results from sample 96DH102 (T. Moore, 2013, personal commun.). Miller et al. (2013) demonstrated results from sample 96DH102 are statistically indistinguishable from results from Triassic samples AE-2 (Miller et al., 2006) and C403752 (Omma et al., 2011) from the northern Sverdrup Basin. On the basis of similarity with these Sverdrup Basin strata and dissimilarity with strata from the northeast Brooks Range, we suspect that detrital zircons from sample AE-2 were mounted and analyzed twice for the Miller et al. (2006) study, once as AE-2 and once, erroneously, as 96DH102, and therefore we consider the published 96DH102 results of Miller et al. (2006) suspect.

DISCUSSION

Cawood et al.’s (2012) observations of a pronounced disparity between crystallization ages of detrital zircons and depositional ages of host strata in rifted and/or passive-margin tectonic settings are exemplified by our results (Fig. 5). The contrast in detrital zircon populations between the Mississippian Endicott Group and Pennsylvanian Lisburne Group strata, followed by an overall consistency in the detrital zircon populations from Pennsylvanian to Middle Jurassic time can be best explained by a significant change in the sediment source region that occurred between Mississippian and Pennsylvanian time. We attribute this change to the burial of a proximal source region that was eroding a large proportion of Devonian age zircons and subsequent derivation of sediment over the next ~150 m.y. from a more distal source region that was eroding an older and more heterogeneous population of zircons. Within the well-studied context of the depositional environments of Ellesmerian and Beaufortian strata, the detrital zircon data from post-Mississippian strata reflect efficient mixing of multiple sources with heterogeneous age populations as would be expected in a marine shelf setting.

In the Inigok #1 well (Fig. 2), the predomiance of Devonian age zircons in the sample from the Endicott Group, coupled with the presence of subangular and coarse-grained quartz in this sample (Fig. 5; Appendices B and C) suggest it was derived from a source region that contained Devonian plutonic and/or volcanic rocks. The East Teshekpuk #1 well (not sampled in this study) ~65 km north of the Inigok #1 well (Fig. 2) penetrated a granitic pluton of probable Devonian age (332 ± 10 Ma K-Ar age on K-feldspar, Bird et al., 1978; and Late Devonian U-Pb age on zircon, T. Moore, 2013, personal commun.) beneath the pre-Mississippian unconformity, with a weathered rind that is onlapped by latest Mississippian carbonate strata of the.

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<td>Keikuktur Formation</td>
<td>Mississippian</td>
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Note: Latitude/longitude datum is WGS84. In location column, #1 is short for “Test Well No. 1.” MD is measured depth taken from well reports (Brockway, 1983; Haywood and Brockway, 1983a, 1983b; Husky Oil NPR Operations Geology Department, 1983). Assignment of lithostratigraphic interval and age based on well reports and additional biostratigraphy and palynology of Mickey et al. (2006). N/A—not applicable.

*Supplemental Table. Compiled zircon U-Pb LA-ICP-MS results of analyzed samples. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GEOS1027.S1 or the full-text article on www.gsapubs.org to view the Supplemental Table.
Lisburne Group (Bird et al., 1978; Dumoulin, 2001). The Okpilak Batholith and associated Jago Stock in the northeastern Brooks Range have similar onlap relationships with respect to the unconformity encountered in the East Teshekpuk #1 well, and have yielded U-Pb ages of 380 ± 10 Ma (Dillon et al., 1987). Farther east in the northern Yukon, 360–375 Ma plutons that intrude the Franklinian strata of the Romanzof belt also exhibit analogous onlap relationships as reported by Lane (2007).

The detrital zircon populations from the Lisburne Group sample in the Ikpikpuk #1 well and the rest of the strata sampled contain significantly fewer grains with Devonian crystallization ages than the Inigok #1 Endicott Group sample population (Fig. 5). The onlap relationship of latest Mississippian Lisburne Group strata across weathered granite in the East Teshekpuk #1 well is evidence that exposed Devonian granite had been locally onlapped and...
buried by the time down-dip Lisburne carbonate strata sampled in the Ikpikpuk #1 well were being deposited.

Once this basement plutonic source was buried by the Lisburne carbonate platform, the predominant source(s) of clastic input into the Arctic Alaska Basin contributed zircon populations with characteristically well-mixed age population distributions (Fig. 5). The relatively low variability over a wide geographic area (Figs. 2 and 5) and through time (Figs. 3 and 5) provides a critical constraint on the reconstruction models. The very minor differences in the spectra of these detrital zircon populations and their possible stratigraphic interpretations are discussed in more depth in Appendix D.

Detrital zircon populations of the Early Triassic Ivishak Formation are significantly more varied from sample to sample than any other post-Mississippian unit studied. These samples yield age spectra with ~15%–32% crystallization ages <750 Ma, whereas age spectra from the other post-Mississippian strata yield ~17%–23% crystallization ages <750 Ma (Fig. 5). Basin-scale effects on sediment sampling (Ingersoll et al., 1993) have been demonstrated as a primary control on the homogenization of detrital zircon populations within a basin (Degraaff-Surpless et al., 2003; Link et al., 2005). Accordingly, the relative heterogeneity of the point-sourced Ivishak Formation (e.g., Wilson et al., 2001a) reflects derivation from first-order sources and deposition in a second-order fan-delta system, whereas the relative homogeneity of Lisburne Group, Echouka Formation, and Karen Creek–Sag River Formation strata is due to efficient mixing of clastic detritus in a third-order shelfal environment (e.g., Barnes, 2001; Bird, 2001). The rounded, frosted, and commonly fragmental nature of detrital zircon grains from most samples (Appendix C) is interpreted to be the result of mechanical abrasion, as would be expected in a nearshore (third-order) environment.

A contrast in detrital zircon populations from the latest Triassic to Early Jurassic Karen Creek–Sag River Formation strata to the Early to Middle Jurassic Simpson Sand of the Kingak Formation is indicated by a pronounced decrease in the proportion of Phanerozoic age zircons in the sampled population, in that only ~8% of zircon ages from the Simpson Sand sample yielded <750 Ma age (Fig. 5). Because only one sample of Simpson Sand was collected and analyzed, interpretations related to this observed change are speculative. Like the Ivishak Formation, the Simpson Sand is interpreted as point sourced (Houseknecht, 2001) and therefore may not be as well mixed (and thus less representative of source region for a time interval) as Karen Creek–Sag River Formation shelf sands that underlie it. In general, however, the age spectrum of the Simpson Sand is similar to most of the post-Endicott strata analyzed, indicating a major change in source region had not occurred by the time these strata were being deposited. Therefore the source region of post-Endicott strata was generally unchanged during the rest of Ellesmerian megasequence deposition and into the early stages of the deposition of the Beaufortian megasequence.

**Implications for Pre–Canada Basin Paleogeography**

A comparison of detrital zircon results presented here with previously published results from Middle to Late Devonian foreland and intramontane basin strata from the Canadian Arctic Islands (Anfinson et al., 2012a; Malone, 2012) and the Late Devonian Imperial Formation of northwestern Laurentia (Beranek et al., 2010a; Lemieux et al., 2011) illustrates remarkable similarities between the detrital zircon populations of Mississippian to Middle Jurassic strata of northern Alaska and these Middle to Late Devonian age synorogenic strata (Fig. 6). The prominent age peaks in all samples include those at 360–390 and 415–470 Ma, a lack of ages in the 750–850 Ma time span, a broad distribution of ages from 0.9 to 2.1 Ga, less pronounced maxima between 2.5 and 2.8 Ga, and the presence of non-Laurentian affinity ages between 500 and 750 Ma. The most salient contrasts in detrital zircon age populations are the greater relative proportions of 500–750 Ma zircons in the Canadian strata, the prominence of a ca. 965 Ma peak in the Okse Bay Formation that is present but minor in the other strata, and the greater percentage of zircons forming a

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**Figure 6. Illustration of the similarities in detrital zircon age spectra from the Devonian clastic wedge from studies in the Canadian Arctic Islands (Okse Bay Formation from Malone, 2012, and clastic interval III from Anfinson et al., 2012a), northwest Yukon Imperial Formation (Beranek et al., 2010a; Lemieux et al., 2011), and compiled results from this study as (A) relative probability distributions (Gehrels, 2010a) and (B) cumulative probability plots (Gehrels, 2010b).**
prominent age peak at ca. 1.8 Ga in the Okse Bay Formation, Imperial Formation, and northern Alaska data, which is less well defined in the foreland basin strata of the Canadian Arctic (Fig. 6). However, for the purpose of testing reconstruction models, these contrasts are less significant than the overall gross population similarities between the along-trend exposures of Middle to Late Devonian age synorogenic strata from Canada and the younger passive margin strata in northern Alaska (Fig. 6).

These new data provide fresh insights regarding the validity of the paleogeographic and tectonic reconstructions portrayed in Figure 4. Lane's (2007) model, which shows a vast region of accreted terrane(s) bordering both the Canadian and Alaskan margins (Fig. 11 in Lane, 2007), implies that sediments in northern Alaska should have been derived from this proposed landmass and that only the northeast Brooks Range area of northern Alaska would have been proximal to Laurentian margin sources. Therefore, this model predicts provenance differences along strike of the northern Alaskan margin that are clearly not seen in our data.

To a lesser extent, the positioning of Arctic Alaska in the Grantz et al. (2011) and Cocks and Torsvik (2011) models has similar implications, in that the input of non-Laurentian sources should become more significant as one moves from east to west along the northern Alaska margin. Cocks and Torsvik (2011) specify that the eastern part of Arctic Alaska (allochthonous to Laurentia in their model) was accreted in an Early to Middle Devonian oblique collision, filling a vast foreland basin region with Middle to Late Devonian clastic wedge sediments. However, Strauss et al. (2013) presented fossil and detrital zircon data that demonstrated a pre–Late Devonian Laurentian origin for the northeast Brooks Range, distinct from parts of western Arctic Alaska that have lower Paleozoic strata and Neoproterozoic basement linked to the edge of Baltica (Amato et al., 2009; Miller et al., 2010, 2011). Thus, Cocks and Torsvik's (2011) categorization of all of pre–Late Devonian Arctic Alaska as allochthonous with respect to Laurentia is at odds with the conclusions of Strauss et al. (2013).

Conversely, the model of Embry (1990) implies that northern Alaska was part of the Franklinian mobile belt, and that Late Devonian to Early Mississippian cratonward propagation of the Ellesmerian deformation front could have inverted the Devonian foreland clastic wedge and underlying Franklinian Basin strata to act as a source region for Ellesmerian and younger Beaufortian strata in northern Alaska (Figs. 3, 4, and 6). The well-constrained northward progressive onlap and southerly sediment transport directions for Ellesmerian and lower Beaufortian strata in NPRA (e.g., Bird, 2001) restrict the source region for clastic material in northern Alaska to an area north (present-day coordinates) of the locations of samples analyzed (for further detailed discussion, see Appendix D). This constraint on sediment pathways, in conjunction with the detrital zircon data, is fundamental to the case that Ellesmerian and lower Beaufortian strata in northern Alaska could not have been derived from non-Laurentian continental terranes accreted in Paleozoic time (Lane, 2007; Colpron and Nelson, 2009) but could have been derived from the reworking of Devonian foreland clastic wedge and underlying Franklinian Basin strata. On the basis of detrital zircon studies, paleocurrent analysis, and whole-rock isotopic signatures, Anfinson et al. (2012a, 2012b) demonstrated that the Devonian foreland clastic wedge of the Canadian margin contains sediment with fluvial sources in the Greenland Caledonides as well as from Crockerland (i.e., the northern “non-Laurentian” landmass uplifted in the Ellesmerian orogeny). Our data indicate there is a lesser proportion of material that appears to be derived from non-Laurentian (Crockerland) sources in northern Alaska strata than in the Devonian foreland clastic wedge of Canada, but on the whole both Alaskan and Canadian detrital zircon populations yield Laurentian affinity results (Fig. 6). Thus, it seems improbable that accreted non-Laurentian continental terranes were the source for sediments in NPRA, as one would expect detritus shed from such terranes to be dominated by the Crockerland detrital zircon signature (e.g., prominent 500–700 Ma zircon populations) as documented by Anfinson et al. (2012a, 2012b) in the Parry Islands and Blackley Formation strata.

The presence of an angular unconformity beneath the uppermost synorogenic foreland basin strata (Parry Islands Formation) in the Devonian foreland clastic wedge of Arctic Canada records the Late Devonian (Famennian) propagation of the Ellesmerian orogenic front into the foreland basin, implying that a significant topographic high existed outboard (present-day north) of the Devonian foreland basin (Embry, 1991). This high would preclude the dispersal of trans-Greenland fluvial sediments into the western region of northern Alaska as suggested by the model of Lane (2007). Conversely, the distinctive mixes of trans-Greenland and Crockerland sources seen in detrital zircon spectra from the Devonian foreland clastic wedge in Arctic Canada and northwest Laurentia are remarkably similar to the spectra in our samples from Alaska (Fig. 6), supporting the model of Embry (1990) in which Alaska lay along strike of the axis of the foreland basin and outboard of Banks Island.

The intermediate position of Arctic Alaska in the models of Grantz et al. (2011) and Cocks and Torsvik (2011) implies that the northeast Brooks Range was in closer proximity to the Franklinian mobile belt than the NPRA region (Fig. 4). However, age-equivalent detrital zircon populations from NPRA and the northeast Brooks Range yield remarkably similar age spectra despite the >750 km along-strike distance (e.g., Late Triassic Karen Creek and Sag River results, Fig. 5). Thus both regions along the Arctic Alaska passive margin were being fed from sources with similar detrital zircon populations. Figure 6 illustrates the similarity of detrital zircon populations in Middle to Late Devonian age synorogenic strata along strike of the Franklinian mobile belt, providing compelling evidence that reworking of these strata provided the detrital zircon source for the younger passive margin strata in Arctic Alaska. Because these reconstructions restore the northeast Brooks Range portion of the Alaska margin against the Anderson Plain in a nearly orthogonal orientation relative to the trend of the clastic wedge of the Ellesmerian orogeny (Fig. 4), they are considered less viable alternatives to the reconstruction of Embry (1990) and not considered in further discussion.

Tectonic Evolution of Northern Alaska

The paleogeographic reconstruction of Embry (1990) implies that NPRA and the northeast Brooks Range occupied positions that were adjacent to the stable shelf margin of Laurentia and were, upon reconstruction, positioned along the Canadian margin between Prince Patrick Island and the Anderson Plain (Fig. 4). The detrital zircon data from northern Alaska provide several independent lines of evidence that support Embry’s (1990) reconstruction. More exact placement of northern Alaska relative to the Canadian margin, however, is not specified by this study.

Combining our new data with published stratigraphic and structural data from both Alaska and Canada has yielded a model for the tectonic evolution of northern Alaska that satisfies the Embry (1990) reconstruction (Figs. 7–9). Figure 7 illustrates the proposed continuity of the Romanzof orogen (with along-strike mobile belts on Pearya and presumably in Crockerland) that brought non-Laurentian terranes together with the passive margin of northern Laurentia. Figure 8 illustrates the potential synchronicity between uplift of Devonian plutons in northern Alaska and Canada, propagation of the Ellesmerian deformation front into the Devonian foreland basin, inversion and fluvial reworking of the proximal foreland wedge, and deposition of the earliest strata of...
the Ellesmerian sequence in Alaska during Late Devonian time. Figure 9 illustrates the postorogenic and thrust belt of the Devonian foreland basin (Canada reference frame). Early Paleozoic distal passive margin strata of the Franklinian megasequence in northern Alaska were weakly metamorphosed by burial beneath a tectonically-thickened sediment load of the foreland clastic wedge of the Romanzof (early Ellesmerian) orogeny, which became inverted as deformation propagated cratonward during the (late) Ellesmerian orogeny (Figs. 7 and 8). The broad margin-parallel structural culmination associated with the Ellesmerian orogeny confined the foreland sediment fairway that funneled the Devonian foreland clastics along the Canadian Arctic margin toward the Yukon region of northwest Laurentia (Fig. 8). As the Ellesmerian thrust front propagated cratonward into its own foreland basin (Figs. 7 and 8), the clastic wedge and underlying Franklinian Basin strata were cannibalized and redeposited in the parts of the basin

Figure 7. Early to Middle Devonian Romanzof and early Ellesmerian orogenies, plotted on identical base map used in Figures 8 and 9. Reconstruction of the position of northern Alaska with respect to the Canadian Arctic margin is from Embry (1990) plotted on gravity base map of McAdoo et al. (2008). Distribution of coarse clastic sedimentation (stippled pattern) based on Anfinson et al. (2012a) for Canadian Arctic Islands, Kumar et al. (2011) for Chukchi Sea region, Churkin (1975) and Mauch (1987) for National Petroleum Reserve-Alaska, and Kelley (1999) and Lane (2007) for northeastern Brooks Range. Thrust belt depiction is approximation of the maximum cratonward propagation of deformation during this time. Stable shelf margin (gray dashed line) from Miall (1976). Paleotransport direction (black arrows) generalized from outcrop data of Anfinson et al. (2012a) and Lane (2007) and seismic data of Kumar et al. (2011) and Mauch (1987). Generalized location of inferred highland regions denoted by hill-shaped symbols. BA—Banks Island; PP—Prince Patrick Island; AH—Axe Heiberg Island; EL—Ellesmere Island. Inset on time intervals describes general tectonic and/or depositional environment for respective regions. AA—Arctic Alaska; W. and E. CAI—western and eastern Canadian Arctic Islands; CL/P—Crockerland/Pearya.

Figure 8. Late Devonian (ca. 365 Ma) interpretation of paleogeographic elements and depositional system(s) associated with propagation of Ellesmerian orogeny, plotted on identical base map used in Figures 7 and 9. Location of clastic wedge strata (outlined) and paleocurrent directions in Canadian Arctic Islands are from Anfinson et al. (2012a) and Mayr (1992). PI4 symbol denotes general location of Anfinson et al. (2012a) sample discussed in text and Figure 10. OB symbol denotes location of Okse Bay strata of Malone (2012). Propagation of thrust front beyond National Petroleum Reserve—Alaska and onto Barrow Arch is based on seismic data of Mauch (1987). Inferred highlands symbolized as in Figure 7. Latest Devonian uplifted regions of Canadian Arctic Islands (Lerand, 1973) denoted (AKL—Aklavik arch; CC—Cape Crozier anticline; PP—Prince Patrick uplift). Location and paleocurrent directions of Kanayut–Hunt Fork depositional system are from Nilsen and Moore (1984). North Slope pluton locations (ET—East Teshekpuk; OK—Okpilak; RB—Romanzof belt) from Bird et al. (1978) and Lane (2007). Canadian Arctic Island pluton locations (RF—Rens Fiord; PH—Phillips Inlet) from Trettin et al. (1992). Inset abbreviations same as Figure 7.
Unroofing of the pluton may have initially shed the East Teshekpuk pluton in NPRA (Fig. 8). The ca. 375 Ma age peak, nearly identical to the dominant age population of zircons in detrital zircon data from a sample from Prince Heiberg Island from Moore et al. (2002) and Embry and Beauchamp (2008) are shown as red asterisks. Zircon icons denote sample locations compared in Figure 10 (keyed by number and color). Location of NW Yukon samples discussed in text and shown in Figure 8 are ~400–1500 km farther south and east of figure extent (Beranek et al., 2010b). Latest Ellesmerian deformation front and stable shelf margin reproduced from Figure 4. Inset abbreviations same as Figure 7.

As a potential example of northern Alaskan sources in the Devonian foreland clastic wedge of Canada, Anfinson et al. (2012a) reported detrital zircon data from a sample from Prince Patrick Island (PI-4) that contains abundant Devonian age zircons. A majority of these zircons yield a ca. 375 Ma age peak, nearly identical to the dominant age population of zircons in the Endicott Group sample thought to come from the East Teshekpuk pluton in NPRB (Fig. 8). Unroofing of the pluton may have initially shed detritus toward the Canadian Arctic Islands in latest Devonian time, whereas later in Mississippian time the exposed pluton was a local source for Endicott Group strata in Alaska. Other possible sources of these Late Devonian zircons are 360–370 Ma plutons and dikes exposed on northern Axel Heiberg and Ellesmere Islands (Trettin et al., 1992) or 360–375 Ma plutons that intrude the Romanzof belt in the northern Yukon (Lane, 2007), although zircons from plutons in the Romanzof belt would have needed to have been transported against the inferred axial transport direction of the clastic wedge (Fig. 8).

Regardless of the source of the ca. 375 Ma zircons in Anfinson et al.’s (2012a) sample, rotation of Alaska back to the Canadian margin restores the Late Devonian plutons in Alaska and Canada to form a linear trend (Fig. 8) that is known to have been unroofed soon after intrusion of the plutons.

**Devonian Rifting and Subsidence of Arctic Alaska**

During Late Devonian to Early Mississippian time, the Barrow Arch acted as a hinge zone for the newly formed south-facing (present-day reference) Arctic Alaska continental margin (Fig. 8). The Late Devonian uplift, erosion, and subsequent subsidence are attributed to rifting of the southern margin (present-day) of Arctic Alaska in Middle to Late Devonian time (Anderson et al., 1994; Moore et al., 1994). The onlap of Late Devonian plutons by Middle Mississippian (Visean) carbonates in NPRB and in the northeast Brooks Range is incontrovertible evidence of a period of significant Late Devonian to Early Mississippian uplift and erosion in northern Alaska followed by subsidence (Fig. 8). Rifting provided accommodation for proximal and localized redeposition of Devonian foreland clastics eroded from the inverted structural culmination to the north into numerous subbasins in NPRB (Kirschner and Ryterski, 1988; Wilson et al., 2001b). Farther south, the Late Devonian Kanayut Conglomerate–Noatak Sandstone–Hunt Fork Shale sequence (Fig. 8) was deposited along the nascent continental margin, likely sourced from reworking of older orogenic deposits (Moore et al., 1994).

Along the Mackenzie Delta–Prince Patrick Island segment of the Canadian margin, the Aklavik arch, Cape Crozier anticline, and Prince Patrick uplift all form a broad belt of Late Devonian structural highs (Fig. 8), some of which are onlapped by late Paleozoic strata (Lerand, 1973). Thermal history data indicate pre-Cretaceous removal of several kilometers of overburden at numerous locations along this structural trend, compatible with our proposed inversion and erosion of the Devonian foreland clastic wedge (Embry, 1991; Gentzis et al., 1996). This inference is supported by recent seismic mapping offshore Banks Island that documents extensional faulting and clastic wedge deposition in Late Devonian to Early Mississippian time followed by erosion and a depositional hiatus lasting until at least Jurassic time (Bjerkebæk and Sultan, 2013). Restoring Arctic Alaska to the Canadian Arctic margin allows the Late Devonian uplift, erosion, and extensional faulting to be a consequence of rift shoulder uplift related to the opening of the Angayucham Ocean basin (e.g., Patton and Box, 1989).

By Early Mississippian time, thermally subsiding regions of northern Alaska that had been eroded during Late Devonian time became active depocenters, with fluvial and nearshore depositional systems filling half-graben basins along the length of the Arctic Alaska margin (Kirschner and Ryterski, 1988; Wilson et al., 2001b; Sherwood et al., 2002). Detrital zircon...
data from a sample of the Kekiktuk Formation of the Endicott Group (Fig. 5) strongly support derivation of sediments at this time from areas that included Devonian plutonic rocks such as the local Franklinian “basement” of northern Alaska (Dumoulin, 2001) (Fig. 8). The abrupt change in the age distribution of detrital zircons following the onlap and burial of locally exposed Franklinian strata (Fig. 5) reflects the headward expansion of drainage networks landward of the onlap edge into regions underlain by uplifted Devonian foreland clastic wedge strata (Fig. 9). Embry’s (1990) restoration of northern Alaska places the truncated northwestern end of seismically mapped Ellesmerian onlap trends near Point Barrow in a position opposite those on Prince Patrick Island in Canada (Fig. 9) (Toro et al., 2004). In using these features as tie-points, the source region of Ellesmerian strata in northern Alaska becomes limited to the “inverted foreland basin” region in Figure 9.

**Sverdrup Basin–Hanna Trough–Arctic Alaska Basin Continuity**

In the eastern Canadian Arctic Islands, Late Carboniferous subsidence to form the Sverdrup Basin created a new depocenter roughly parallel to the trend of the restored Arctic Alaska continental margin (Fig. 9). At its western end, the Sverdrup Basin turns and is truncated at the Canada Basin margin. According to Embry’s (1990) model, the Sverdrup and Arctic Alaska Basins were once continuous and linked via the Hanna Trough. The detrital zircon signatures of Triassic and Jurassic strata in northern Alaska are remarkably different from signatures of time-correlative strata that were deposited on the opposite (outboard) flank of the Sverdrup Basin–Hanna Trough–Arctic Alaska Basin axis (e.g., Mesozoic strata at Cape Lisburne and on northern Axel Heiberg Island) but remarkably similar to signatures from the basin flank bordering northwestern Laurentia (Figs. 9 and 10). In the reconstructed framework, Triassic and Jurassic strata onlap the Sverdrup Basin–Hanna Trough–Arctic Alaska Basin axis (i.e., separated by the basin axis from the Laurentian margin) were derived from source regions containing latest Paleozoic and Mesozoic age detrital zircons, whereas in coeval strata inboard of this axis the youngest grains are Paleozoic (Figs. 9 and 10). Exposed parts of the Chukchi Platform were likely sources for strata at Cape Lisburne and in the western Hanna Trough (Moore et al., 2002; Sherwood et al., 2002), while the low-lying landmass of Crockerland fed the outboard margin of the Sverdrup Basin (Emby, 2009) (Fig. 9). The apparent isolation of the inboard (Laurentia side) strata, in conjunction with the striking similarity between detrital zircon spectra of the Ellesmerian megasequence, Canadian Arctic Islands Devonian foreland clastic wedge and Imperial Formation (Fig. 6) support the notion that Ellesmerian megasequence strata in northern Alaska were derived from inverted and eroded Devonian foreland wedge and Franklinian Basin strata initially deposited along the Canadian Arctic margin prior to the rift opening of the Canada Basin.

**CONCLUSIONS**

Detrital zircon geochronology provides an effective method of testing competing models for the pre-opening paleogeography of the Canada Basin. The detrital zircon signatures of Mississippian to Jurassic age strata from Axel Heiberg Island, Canada (1) Miller et al., 2006; Omma et al., 2011 Triassic-Jurassic (n=528)

Cape Lisburne, Alaska (2) Miller et al., 2006 Triassic (n=187)

S. Ellesmere Island, Canada (3) Miller et al., 2006 Triassic (n=86)

NPRA, Alaska (4) This study Triassic-Jurassic (n=435)

NE Brooks Range, Alaska and Yukon (5) This study Triassic-Jurassic (n=354)

NW Yukon, Canada (6) Beranek et al., 2010b Triassic (n=609)

**Figure 10.** Detrital zircon results from this study and previously published data from the reconstruction time interval depicted in Figure 9 (numbers in parentheses next to sample labels are keyed to locations). (A) Relative probability plots of detrital zircon spectra (Gehrels, 2010a) from outside of (top two spectra) and internal to (bottom four spectra) proposed Sverdrup Basin–Hanna Trough bathymetric barrier (Miller et al., 2006; Beranek et al., 2010b; Omma et al., 2011; this study), illustrating the lack of younger than 350 Ma ages in internal versus external strata. (B) Same data shown as cumulative probability plots (Gehrels, 2010b).
similar through time and for >750 km along strike. Additionally, the resultant age spectra bear strong resemblance to age spectra from the Middle to Late Devonian foreland clastic wedge of the Franklinian mobile belt exposed in the Canadian Arctic Islands and the Late Devonian Imperial Formation in northern Yukon Territory. The following observations and interpretations are most consistent with models in which the current position of the northern Alaska margin has been rotated at least 55° counterclockwise with respect to the conjugate Canadian margin during opening of the Canada Basin.

The pre-opening paleogeographic reconstruction of the Canada Basin margins by Embry (1990) positions northern Alaska adjacent to the Franklinian mobile belt and along strike of the Middle-Late Devonian to Early Mississippian foreland basin (Devonian foreland clastic wedge) of the Canadian Arctic Islands and northern Yukon Territory. The restored Alaskan and Canadian margins of the Canada Basin occupied relatively more hinterland and foreland positions, respectively, but are parts of the same Early Devonian to Early Mississippian deformational belt. Early to Middle Devonian synorogenic clastic strata in northern Alaska were derived from the Romanzof orogen that was an along-strike continuation of coeval early Ellesmerian deformation affecting the Arctic margin of Canada. Late Devonian to Early Mississippian inversion of the Franklinian Basin in northern Alaska and the foreland clastic wedge in Arctic Canada was the result of continued propagation of deformation into the foreland basin. Cooling and unroofing of Late Devonian granitic plutons in Arctic Alaska and along the outboard portion of the Franklinian mobile belt in Arctic Canada was coeval with this inversion and contemporaneous with the onset of rifting across Arctic Alaska. The preponderance of Late Devonian age zircons in the uppermost foreland clastic wedge strata of Arctic Canada and the lowermost postorogenic strata in Arctic Alaska ties both margins to this rapidly exhumed belt of Late Devonian plutonic rocks.

In general, the detrital zircon results are consistent with the transition from rift to passive margin setting leading to deposition of the Ellesmerian and lower Beaufortian megasequence strata. The most likely sources of pre-Devonian detrital zircon populations in Ellesmerian and lower Beaufortian megasequence strata in Arctic Alaska were the inverted Devonian foreland clastic wedge and underlying Franklinian Basin strata of the Ellesmerian foreland basin. Before the Canada Basin formed, the continuous axes of the Sverdrup Basin, Hanna Trough, and Arctic Alaska Basin isolated the northern Alaska shelf and kept it from receiving clastic input from non-Laurentian source regions such as those feeding the Cape Lisburne region of Alaska and the northern Sverdrup Basin of Canada.

APPENDIX A: SAMPLE SELECTION AND ANALYTICAL METHODS

Sampling interval targets were selected on the basis of availability and suitability of conventional drill core and hand samples archived at the Alaska Geologic Materials Center in Eagle River, Alaska. Sampled strata come from distal and proximal portions (with respect to the margin) of the Ellesmerian megasequence. The most distal section sampled was the Inigok #1 well, and the most proximal section sampled was from the East Simpson #1 well. Because onlap progressed northward during Ellesmerian deposition, the ages of Ellesmerian strata penetrated in the proximal wells represent a narrower range of ages than sequences penetrated in distal wells. For example, the lowermost Ellesmerian core in Pearl #1 comes from the Permian Echouka Formation, which unconformably overlies the Franklinian sequence in this well. Conversely, in distal wells such as Inigok #1, Franklinian strata were never penetrated (total drilled depth >6000 m). In the Sadlerochit and western British Mountains of the northeast Brooks Range, Triassic strata depositionaly overlie Lisburne Group carbonate rocks, allowing the inference that these Triassic strata were deposited distal to the northern onlap edge of the Lisburne Group carbonates.

Within this framework, 12 samples, eight from NPRA conventional core and four from outcrop in the northeastern Brooks Range, were analyzed for detrital zircon geochronology (Table 1). Detailed sample descriptions based on previously published reports are included in Appendix B. Zircons were separated from ~25 cm² and larger samples by hand brushing with steel mortar and pestle. Crushed material was sieved at 0.25 mm, and the >0.25 mm residue was crushed and sieved again. This process was repeated until ~90% of the rock volume was less than 0.25 mm. A Gemini table was used to perform density-based separation on the <0.25 mm crushed fraction of the rock. The heavy fractions were then rinsed with deionized water, soaked for 24 hours in 3% acetic acid, rinsed again with deionized water, soaked for 24 hours in hydroperoxide, rinsed a third time with deionized water, soaked for 24 hours in hydrofluoric acid, rinsed a fourth time, and dried at 40 °C. Dried fractions were run through a Frantz magnetic separator to remove magnetic minerals, and a final density separation was performed using the heavy liquid methylene iodide.

Zircon grains were prepared for U-Th-Pb geochronology by arranging zircon age standard (Sri Lanka, University of Arizona via laser ablation–induc-
et al., 2001b). In this well, the biostratigraphic age of the Kekiktuk Formation has been bracketed between Kinderhookian and Visean (ca. 360–326 Ma) (Walker et al., 2012). Paleoforaminifera studies (Mickey et al., 2006). Kekiktuk strata consist of coal, shale, sandstone, and conglomerate layers representing a fluvial-deltaic environment. Based on dipmeter logs, all of the Endicott and portions of the Lisburne Group strata penetrated by the Inigok well are tilted, with bed dips changing from horizontal in upper Lisburne strata to ~30° at the bottom of the wellbore (Haywood and Brockway, 1983a).

**Lisburne Group—Wahoo Limestone**

Sample IK-LS from the Lisburne Group was taken from core #12 of the Ipiupkuk #1 test well from the measured depth interval 12,743–12,753 ft. The interval sampled consists of a shaley silstone at the base that grades up into well-sorted skeletal grainstone and has been assigned to the Pennsylvanian portion of the Lisburne Group, equivalent in part to the Wahoo Limestone of the Brooks Range (Dumoulin and Bird, 2001). An Atokan age (318–311 Ma) has been determined for this fossiliferous assemblage (Dumoulin and Bird, 2001; Mickey et al., 2006). The depositional environment of this interval has been interpreted as a shallow marine shelf that was undergoing a gradual shallowing and decrease in clastic input during Pennsylvanian time (Brockway, 1983; Dumoulin and Bird, 2001). Northeast of the Ipiupkuk well, significant input of quartz, chert, and minor feldspar detritus into the Pennsylvanian carbonate depositional system is noted in several wells in NPRA (Dumoulin and Bird, 2001).

**Sadlerochit Group—Echooka Formation**

Sample PR-EC from the Echooka Formation was taken from core #1 of the Pearl #1 Test Well from the measured depth interval 9490–9499 ft. This section is Late Permian in age and is composed of fine-grained calcareous sandstone that locally contains well-rounded medium- to coarse-grained quartz and chert as grit in the outer shelf. The detrital zircon geochronology results (Haywood and Brockway, 1983a; Wilson et al., 2001a). The Echooka represents the lowermost lithostratigraphic unit of the Sadlerochit Group, the base of which is defined by an unconformity that progressively cuts Lisburne, then Endicott, then Franklinian strata from south to north (Moore et al., 1994). The unconformity is a marine transgressive surface, above which sits an upward coarsening succession of shale to conglomerate that was deposited during southward progradation of fluvial-deltaic systems. In the Pearl well, the pre-Echooka unconformity sits on a steeply dipping sequence of gray argillite that is at least Devonian in age (Dumoulin, 2001). The depositional environment of the portion of the Echooka represented in core #11 was an extensively bioturbated offshore to lower shoreface marine setting that received periodic influxes of coarse clastic material during storm events (Wilson et al., 2001a). The top of the Echooka Formation is characterized by an onset of rapid sedimentation resulting in the deposition of fine-grained mudstone and silstone of the Kavik Shale (Wilson et al., 2001a).

**Sadlerochit Group—Ivishak Formation**

Five samples of the Ivishak Formation were analyzed for this study, three of which were collected from wells and two from outcrop. The Ivishak Formation gradually overlies the Kavik Shale of the Sadlerochit Group or sits unconformably on rocks below the pre-Echooka (pre-Permian) unconformity. It is suggested that the Ivishak Formation represents deposition of clastic material delivered from a northerly-sourced, southward-prograding, fluvial-deltaic system of Triassic age (Moore et al., 1994). The Ivishak Formation represents variable depositional environments across the North Slope and includes deltaic and marginal marine mudstone, silstone, and sandstone overlain locally by thin conglomeratic sandstone and mudstone (Moore et al., 1994; Wilson et al., 2001a and references therein).

Samples SM-IV and WB-IV were collected in the northeastern Brooks Range from outcrop in the Sadlerochit Mountains and western British Moun-

tains, respectively. These samples are quartz-rich silstone that have been uplifted and structurally transported northward during Brookian deformation. Mapped relationships at these locations indicate that the Sadlerochit Group overlies Lisburne Group strata, indicating they were deposited south of the regional northern onlap limit of Lisburne Group strata. Sample IK-IV was taken from core #9 of the Ipiupkuk #1 Test Well from the measured depth interval 10,815–10,842 ft and represents a similar distal position along strike of the above samples from outcrop. The Ivishak in the Ipiupkuk core contains a very fine to fine-grained section of quartz-rich sandstone with shale partings and meter-scale, fining upward intervals of coarser sand, pebbles and shale clasts, likely representing deposition in the prodelta region of a prograding delta front (Brockway, 1983). Sample IN-IV was taken from core #15 of the Inigok #1 Test Well from the measured depth interval 12,705–12,735 ft. The Ivishak in the Inigok well consists of interbedded fine sandstone and shale layers that exhibit ripple cross lamination and bioturbation, and contain rip-up clasts, and have been interpreted as proximal delta front facies (Haywood and Brockway, 1983a; Wilson et al., 2001a). Sample ES-IV was taken from core #8 of the East Simpson #1 Test Well from the measured depth interval 7500–7523 ft. The sample is a poorly sorted, sandy, clast-supported conglomerate made up predominantly of chert pebbles, interpreted as being deposited in a bed load-dominated fluvial system such as a braided stream environment (Haywood and Brockway, 1983b; Wilson et al., 2001a). In this well, the base of the Ivishak sits unconformably on the Franklinian sequence and contains coal fragments thought to be derived from uplewan erosion of Endicott strata during Ivishak deposition (Wilson et al., 2001a). The top of the Ivishak Formation records the abandonment or transgression of the fluvial depositional system with deposition of the Fire Creek Silstone and the heterolithic Shublik Formation but has been eroded in places by the Lower Cretaceous Unconformity (e.g., Bird, 1988).

**Sag River and Karen Creek Formations**

Three samples of a prominent sandstone that overlies Shublik Formation were analyzed, two from the northeast Brooks Range and one from an NPRA well. The Sag River Sandstone in the NPRA subsurface and Karen Creek Sandstone onlaps an unconformity that is beyond the limit of Lisburne Group strata, indicating they were deposited south of the regional northern onlap limit of Lisburne Group strata (Brockway, 1983a). Both Karen Creek samples are colorless. The detrital zircon geochronology results (Haywood and Brockway, 1983b; Wilson et al., 2001a). In this well, the base of the Ivishak sits unconformably on the Franklinian sequence and contains coal fragments thought to be derived from uplewan erosion of Endicott strata during Ivishak deposition (Wilson et al., 2001a). The top of the Ivishak Formation records the abandonment or transgression of the fluvial depositional system with deposition of the Fire Creek Silstone and the heterolithic Shublik Formation but has been eroded in places by the Lower Cretaceous Unconformity (e.g., Bird, 1988).

**Simpson Sand of the Lower Kingak Formation**

One sample from the Simpson Sand member of the Kingak Shale, PR-SS, was taken from core #7 of the Pearl #1 Test Well from the measured depth interval 7837–7847 ft. The interval sampled is a very fine-grained silty, glauconitic, argillaceous sandstone with subangular quartz grains (Husky Oil NPR Operations Department, 1983). The age of the Kingak interval that hosts the Simpson Sand is reported as Early to Middle Jurassic based on regional correlation of paleontological data from NPRA wells (Housenkecht, 2001). Stratigraphic geometries of the Lower Kingak have been interpreted as representing multiple progradational and aggradational cycles that resulted in long-lived depositional construction of a point-sourced clastic shelf (Housenkecht, 2001). In northern NPRA, the top of the Lower Kingak is erosively truncated by the Middle Jurassic Unconformity and onlapped by Late Jurassic Upper Kingak Formation strata, signifying the onset of rift-driven base-level changes at this location along the Alaskan Canada Basin margin (Housenkecht, 2001). Thus, the Simpson Sand potentially represents some of the youngest strata of the North Slope derived from a northern source region before the opening of the Canada Basin began.

**APPENDIX C: DETRITAL ZIRCON POPULATION DESCRIPTIONS**

**Endicott Group**

The zircons from the Mississippian Kekiktuk Formation of the Endicott Group range in size from 50 to 200 microns long, are elongate to fragmental (~25% exhibit one or more terminations), moderately to well rounded on crystallographic edges, and are generally colorless. The detrital zircon geochronology results from this sample are unlike any of the other samples analyzed (Fig. 5). The largest portion of the population (n = 31 of 78) yields ages that cluster between 355 and 395 Ma, with a 206Pb/238U weighted mean of 372 ± 3 Ma (2σ, mean square of weighted deviates [MSWD] = 0.9). A slightly older part of the population (n = 12) ranges from 410 to 470 Ma, with age peaks at 415 and 440 Ma. Zircons with crystal-
Karen Creek Formation samples are heterogeneous in Triassic to Early Jurassic Sag River Sandstone and numerous 2.3–3.2 Ga results. Zircons in the 500–750 Ma age range, significant population clusters are similar to those from the Lisburne and Echooka intervals sampled. Approximately 15%–20% of the age results are <750 Ma and fall into 365–480 Ma and 515–730 Ma groups. Roughly 60%–70% of grains analyzed yielded 0.9–2.1 Ga results, with a dominant age peak at 1.8–2.0 Ga that is more apparent in these results than in other stratigraphic intervals (Fig. 5). The remainder of age results span from 2.3 to 3.1 Ga.

**Simpson Sand of the Lower Kingak Formation**

The detrital zircon population analyzed from the Middle Jurassic Simpson Sand of the Lower Kingak Formation contains grains up to 250 microns long that appear well rounded, are generally colorless, and appear fragmental. In contrast to the aforementioned results, the Simpson Sand detrital zircon population is dominated by older grains; 90% of the zircons analyzed yielded 0.95–3.1 Ga age results with a definitive age cluster at 1.8–2.0 Ga. The remainder of the analyses (n = 6 of 80) yielded age results that range between 430 and 680 Ma.

**APPENDIX D: ONLAP CONSTRAINTS ON SOURCE REGIONS**

Remarkable similarity exists between the detrital zircon age spectra from the Pennsylvanian IK-LS sample and Permian PR-EC sample (Fig. 5). The Echooka Formation in the Peard well was deposited on an unconformity developed across Franklinian basement rocks at the well site and overlies progressively younger strata to the south (i.e., Endicott, then Lisburne Group). This relationship offers some constraint to the likely sources for detrital zircons in both the IK-LS and PR-EC samples. Because no Lisburne Group samples were harvested from the Echoka onlap, it is highly improbable that the detrital zircon population of the PR-EC sample was derived from the recycling of zircons from the Lisburne Group. More likely, the clastic influx to Lisburne Group carbonate strata (Dumoulin and Bird, 2001) and the clastic material in the Echooka Formation were both sourced from Franklinian mobile belt strata exposed along shorelines and deeper inland regions. Given that the PR-EC sample was deposited on >50 m of earlier Echooka Formation strata, the exposed Franklinian basement from which the detrital zircons were eroded must have lain north of the Peard well, and therefore, north of the Echooka onlap edge.

As a group, the age spectra from samples of Karen Creek–Sag River strata from both NPRA and northeast Brooks Range are likewise remarkably similar to one another and to the Lisburne-Echooka spectra (Fig. 5). The only salient difference between these two groups of samples is a greater percentage of 1.0–1.3 Ga grains in the Lisburne-Echooka samples versus a greater percentage of 1.8–2.0 Ga grains in the Karen Creek and Sag River (Fig. 5). The similarity of younger Karen Creek and Sag River samples to one another, despite the several hundred kilometer distance between sample localities argues for efficient mixing of clastic material prior to ultimate deposition. The most proximal (relative to onlap edges) Karen Creek sample (EB-KC) was deposited in a location where the Karen Creek Formation sits unconformably above Franklinian strata, providing some control that the source region of this sample must have been from positions shoreward of this contact. Conversely, samples ES-SR and WB-KC were deposited in more distal positions where Eivishak and Lisburne strata onlapped Franklinian strata, respectively. Again, given the similarity in spectra between the three samples, all likely were derived from the same source, which is constrained as lying north of where the Shublik Formation onlaps the Barrow Arch.

Conversely, mapped onlap edges provide a southern limit for rocks that could be the sources of clastic material through time. The uniform detrital zircon age spectra from sample to sample in the Lisburne-Echooka and Karen Creek–Sag River suites demonstrate that the source regions for clastic detritus in these formations likely were present for extensive intervals of time and for long distances along strike of the margin. The increasing proportion of 1.8–2.0 Ga grains and decreasing proportion of 1.0–1.3 Ga grains in the Karen Creek–Sag River interval relative to the Lisburne-Echooka samples may be a function of downcutting into the Franklinian source region (Fig. 5).

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**Mesozoic and Cenozoic Geology of Alaska**

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