Detrital geochronology of pre-Mississippian strata in the northeastern Brooks Range, Alaska: Insights into the tectonic evolution of northern Laurentia

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ABSTRACT

The Arctic Alaska terrane of northern Alaska and Yukon is one of several exotic terranes in the North American Cordillera with putative early Paleozoic connections to the northern Caledonian-Appalachian orogen. The U-Pb and ⁴⁰Ar/³⁹Ar isotopic data from detrital minerals in pre-Mississippian stratigraphic units of the northeastern Brooks Range are presented here to investigate the consequences of Caledonian orogenesis on sediment dispersal trends and the paleogeography of northern Laurentia. Neoproterozoic-Cambrian siliciclastic rocks of the informal Firth River group and the Neruokpuk Formation were most likely deposited along a passive margin that sourced Archean and Paleoproterozoic basement rocks of the Canadian shield and reworked Mesoproterozoic and younger sedimentary units. These strata are overlain by a Lower Ordovician-Lower Devonian succession of fine-grained siliciclastic turbidites, herein referred to as the Clarence River group, which records a prominent shift in provenance most likely associated with the onset of the Caledonian-Appalachian orogeny in northeast Laurentia. U-Pb detrital zircon age populations of ca. 470–420 and 990–820 Ma, along with ⁴⁰Ar/³⁹Ar detrital muscovite ages of ca. 470–430 Ma, support provenance connections with the East Greenland Caledonides, Pearya, and Svalbard. Partially reset ⁴⁰Ar/³⁹Ar ages in these sedimentary successions are linked to low-grade metamorphism associated with the Early-Middle Devonian Romanzof orogeny, a poorly understood tectonic event in the Brooks Range that is possibly associated with the emplacement of an allochthonous oceanic assemblage, herein named the Whale Mountain allochthon.

INTRODUCTION

The expansion of continental margins typically occurs through the process of accretionary tectonics, whereby crustal fragments, or terranes, composed of intraoceanic island arcs, ophiolites, rifted continental fragments, microcontinents, and accretionary complexes are progressively sutured to the edge of a continent (e.g., Dewey and Horsfield, 1970; Coney et al., 1980; Moores, 1982; Saleeby, 1983; Schermer et al., 1984; Şengör et al., 1993). During the Phanerozoic, the Laurentian continent expanded along two major accretionary plate margins: the Caledonian-Appalachian orogen and the North American Cordillera. Numerous plate restorations link these two orogens by proposing that several exotic terranes (e.g., Arctic Alaska, Farewell, Alexander, Klamath-Sierra, and Pearya), now within the North American Cordillera and Canadian Arctic (Fig. 1A), were displaced from the northern Caledonian or paleo-Arctic realm and translated along the northern margin of Laurentia (e.g., Colpron and Nelson, 2011; Cocks and Torsvik, 2011; Miller et al., 2011).

The Arctic Alaska terrane encompasses the Brooks Range, North Slope, and Seward Peninsula of northern Alaska, all of which contain several independent pre-Mississippian and Mesozoic crustal fragments, or subterranes, that host unique stratigraphic sequences (see review in Moore et al., 1994). During the Jurassic and Early Cretaceous, the south-facing passive margin of the Arctic Alaska terrane collided with the Koryukuk arc; this suture zone is marked by the Angayuchum terrane (Fig. 1B), a Devonian-Jurassic assemblage of ophiolitic fragments and pelagic sedimentary deposits (Moore et al., 1994). Some suggest that this suture zone extends westward across the Bering Sea to connect with the South Anyui suture zone of the Chukotka Peninsula, Arctic Russia, forming the composite Arctic Alaska-Chukotka microplate (e.g., Hubbard et al., 1987; Miller et al., 2006; Amato et al., 2009; Moore et al., 2015); however, distinct contrasts in structural styles along both the South Anyui and Angayuchum suture zones may imply different pre-Cretaceous histories for Arctic Alaska and Chukotka (Amato et al., 2015; Till, 2016).

Most Arctic plate models restore the northern edge of Arctic Alaska terrane as the conjugate margin to the Canadian Arctic Islands in Mesozoic time (e.g., Lawver and Scotese, 1990; Grantz et al., 2011). This is achieved by closing the Canada Basin by way of ~60° rotation of Arctic Alaska about a pole located near the Mackenzie Delta during the Early Cretaceous (Gottlieb et al., 2014, and references therein), but many issues remain unresolved regarding the evolution of the Canada Basin (e.g., Lane, 1997; appendix of Lane et al., 2016). A lasting subject of contention also involves the early Paleozoic...
position of the North Slope of Arctic Alaska at the time of the Caledonian-Appalachian orogeny (ca. 470–350 Ma). A commonly accepted model is that pre-Mississippian strata of the northeastern (NE) Brooks Range were deposited along a Neoproterozoic–Early Devonian passive margin that developed north (in present coordinates) of the Yukon block of northwest Laurentia (Fig. 1), before being deformed in the Early–Middle Devonian Romanzof orogeny (e.g., Lane, 1991, 2007; Moore et al., 1994; Cecile et al., 1999; Colpron and Nelson, 2011; Lane et al., 2016). In contrast, others have argued that the North Slope has pre-Mississippian origins in northeast Laurentia, and that it did not attain its pre-Canada Basin position until sometime before the Late Devonian or Early Mississippian (Sweeney, 1982; Dumoulin et al., 2000; Macdonald et al., 2009; Strauss et al., 2013; Cox et al., 2015). Resolving these conflicting interpretations has broad implications for Neoproterozoic–Paleozoic plate reconstructions of the circum-Arctic region and Caledonian-Appalachian orogeny (Strauss et al., 2013); thus, our objective is to present new data pertaining to the structural and stratigraphic evolution of pre-Mississippian rocks in the NE Brooks Range to directly address these competing models.

GEOLOGICAL FRAMEWORK

Pre-Mississippian Stratigraphy of the NE Brooks Range

Pre-Mississippian strata of the North Slope of Arctic Alaska are well exposed in a series of east-west–trending antiforms that compose the NE salient of the Brooks Range (Fig. 2). These units are typically referred to as pre-Mississippian because of their regional truncation by a prominent sub-Mississippian unconformity, a characteristic feature of the NE Brooks Range and North Slope subsurface (Moore et al., 1994). A thick (1000–2000 m) succession of moderately to highly deformed quartzite, phyllite, and argillite called the Neruokpuk Formation (Leffingwell, 1919; Reed, 1968; Lane, 1991; Lane et al., 2016) is widely distributed in the Franklin, Romanzof, British, and Barn Mountains (Fig. 2). The exact age of the Neruokpuk Formation is not well known, but previously it was suggested that it ranges from Neoproterozoic to middle Cambrian (?) based on the occurrence of Oldhamia ichnofossils in the northern British and Barn Mountains of Yukon (Hofmann and Cecile, 1981; Lane and Cecile, 1989; Lane, 1991; Hofmann...
Detrital geochronology in the NE Brooks Range, Alaska

Figure 2. Simplified geologic map of the eastern half of the northeastern Brooks Range. Geology compiled after Reiser et al. (1980), Norris (1981a, 1981b), and Lane (1995). Key structures: WMT—Whale Mountain thrust; RMT—Romanzof Mountain thrust; CDT—Continental Divide thrust (includes the Aichilik Pass thrust of Anderson et al., 1994); FRT—Firth River thrust. Solid teeth on thrust faults indicate disruption of stratigraphic section (old on young); open teeth indicate detachment surfaces along which there has been slip but no disruption of the stratigraphic section (young on old). Abbreviations: Mts.—mountains; YT—Yukon; NT—Northwest Territories; BC—British Columbia.
et al., 1994; Lane et al., 2016; see Table DR1 in the GSA Data Repository1 for a summary of age constraints on pre-Mississippian units of the NE Brooks Range). The Neruokpuk Formation overlies a highly deformed and poorly studied mixed carbonate-siliciclastic succession (Fig. 3), now recognized as the informal Firth River group in the northern British Mountains of Yukon (Lane et al., 2016). In Alaska, the Firth River group includes sequence D and E of Dutro et al. (1972), Domain III of Mull and Anderson (1991), and various carbonate and fine-grained siliciclastic units of Reiser et al. (1980).

In the southern British Mountains of Alaska, a highly deformed and imbricated sequence of predominately fine-grained siliciclastic units, situated below the rocks of the Whale Mountain allochthon, disconformably overlies the Neruokpuk Formation. In the Demarcation Point quadrangle, Reiser et al. (1980) divided these deposits into the following four map units: chert and phyllite (Ccp), calcareous siltstone and sandstone (Css), dark gray to black shale locally metamorphosed to phyllite (map unit Cp), and a subordinate lithic sandstone unit (Cs). These map units were all assigned a Cambrian age based on a single locality of poorly preserved echinoderm debris and their assumed stratigraphic position beneath the Whale Mountain volcanic rocks (Fig. 3; Reiser et al., 1980). Similar packages of interbedded chert, argillite, and lithic sandstone are broadly distributed throughout northern Yukon, particularly near the Alaska-Yukon border along the Clarence and Malcolm Rivers (Kelley et al., 1994; Lane et al., 1995), in the Buckland Hills region along the Firth River (Lane and Cecile, 1989), and in the Barn Mountains (Cecile, 1988; Cecile and Lane, 1991). Age constraints for these strata are provided by a limited number of fossil localities that include lower Ordovician–upper Silurian (Pradoli) graptolites (Lenz and Perry, 1972; Reiser et al., 1980; Lane and Cecile, 1989; Lane et al., 1995; Norford, 1997). The upper age limit of this sequence is locally constrained by two conodont localities: an upper Silurian (Pradoli)–Lower Devonian (earliest Pragian) fauna collected along the Clarence River in Alaska (Lane et al., 1995) and a Lower Devonian (Emsian?) fauna collected at the very northern limit of the British Mountains (Norris, 1986). Both of these samples were collected from isolated talus slopes, so their stratigraphic positions within the greater pre-Mississippian succession remain somewhat ambiguous.

Lane et al. (2016) split these early Paleozoic units of northern Yukon into two general lithostratigraphic successions: a lower graptolitic-bearing succession of interbedded chert and argillite, and an upper dark gray shale and sandstone turbidite package with subordinate chert-pebble conglomerate and limestone. The base of the lower succession is marked by a ridge-forming chert interval that contains Lower Ordovician graptolites (Lane and Cecile, 1989). A similar interval is mapped in the Barn Mountains of Yukon (Cecile, 1988; Cecile and Lane, 1991) and southern British Mountains of Alaska (unit Ccp of Reiser et al., 1980), where it presumably disconformably overlies the Neruokpuk Formation (Dutro et al., 1972). The base of the upper succession is uncertain. Geological mapping in the Buckland Hills region suggests that its contact with the lower succession is discordant (Lane and Cecile, 1989), whereas along the Clarence River and Barn Mountains the boundary between upper and lower succession is gradational (Kelley et al., 1994; Lane et al., 1995) or absent (Cecile, 1988; Cecile and Lane, 1991), respectively. Lane et al. (2016) referred to the lower succession as the Road River Group following correlations with equivalent strata in the Yukon block (Gordey and Anderson, 1993) and the upper succession as the informal Buckland Hills succession.

1GSA Data Repository Item 2016289, Detailed sample descriptions and summary of analytical procedures, Figure DR1 (Photomicrographs of Neruokpuk Formation and Clarence River group samples), Table DR1 (geostratigraphic and fossil age constraints), Table DR2 (sample locations), Table DR2 (U-Pb LA-ICP-MS zircon results from University of California–Santa Cruz), Table DR4 (U-Pb LA-ICP-MS zircon results from Stockholm University), Table DR5 (U-Pb SIMS zircon results from NordSIMS facility), Table DR6 (40Ar/39Ar from University of Alaska Fairbanks), and Table DR7 (single-grain total fusion 40Ar/39Ar ages from University of Alaska Fairbanks), is available at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.
Because we view many of the map relationships as uncertain and the correlations with coeval strata in the Yukon block as suspect, we propose that this entire stratigraphic package should be consolidated into a single lithostratigraphic group, which we informally name the Clarence River group based on a possible type area near the headwaters of Clarence River in the northern British Mountains (Fig. 2). The motivation behind this consolidation is because the recognition and documentation of definitive lithostratigraphic boundaries within the different successions have not been established. Moreover, the group designation allows for subsequent separation of distinct formations with type sections when more geological, geochronological, and biostratigraphic data become available. We tentatively propose that the Buckland Hills succession of Lane et al. (2016) constitutes the uppermost formation of the Clarence River group. The base of the Clarence River group is marked by the prominent Ordovician chert interval that is distributed throughout Yukon and Alaska.

In the Romanzof Mountains and along a linear belt in the southern British Mountains, a thick (>700 m) structural complex composed of basalt flows, discontinuous carbonate beds, and an imbricated package of bedded chert, phyllite, and lithic tuffidites structurally overlie the pre-Mississippian sedimentary successions. In a broad sense the basalt flows, informally named the Whale Mountain volcanic rocks, geochemically resemble ocean-island basalt, showing enrichment in incompatible, large-ion lithophile, and high-field-strength elements (Moore, 1987; Goodfellow et al., 1995). The age of these volcanic rocks is constrained by upper Cambrian (Furongian) trilobites of Laurentian affinity discovered within the discontinuous carbonate beds that locally interfinger with the basalt flows (Dutro et al., 1972). The imbricated and folded package of bedded chert, phyllite, and lithic tuffidite units is widely distributed in the Romanzof Mountains, particularly near the headwaters of the Jago and Aichilik Rivers (Fig. 2). Mull and Anderson (1991) informally named these units the Romanzof chert, and along strike in the southern Franklin Mountains, a lithologically similar imbricated and folded chert package contains upper Ordovician and possible lower Silurian (Llandovery) graptolite fossils (Moore and Churkin, 1984). The tectonic setting and structural relationships of these rocks are not well understood, and because we have yet to document any depositional and/or conformable relationships, we propose that their incorporation into the pre-Mississippian stratigraphy of the NE Brooks Range be ascribed to the emplacement of a now-dismembered thrust sheet, herein named the Whale Mountain allochthon (Figs. 3 and 4).

The pre-Mississippian rocks of the NE Brooks Range are crosscut by a suite of Late Devonian intrusive bodies (e.g., Okpilak batholith and Sedgwick pluton; Fig. 2), which yield U-Pb zircon ages of ca. 380–360 Ma (Dillon et al., 1987; Mortensen and Bell, 1991; Lane, 2007). These intrusive rocks share mineralogical and compositional similarities to S-type granites, implying that they were derived from the partial melting of lower crustal rocks (Sable, 1977; Newberry et al., 1986). Contact relationships with the older country rock, mainly the Nerusokpuk Formation, are abruptly with a limited metamorphic aureole, possibly indicating shallow levels of emplacement and/or a shortage of hydrothermal fluids (Sable, 1977). In many places throughout the field area, the Mississippian Kekiktuk Conglomerate, the basal unit of the lower Ellesmerian sequence (e.g., Moore et al., 1994), overlies with angular unconformity on the pre-Mississippian sedimentary units and Late Devonian intrusive rocks. At the southern edge of the field area, near the headwaters of the Kongakut River (Fig. 2), the Kekiktuk Conglomerate also truncates the Middle Devonian Ulungarat Formation of Anderson et al. (1994), formerly unit Ds of Reiser et al. (1980). The Ulungarat formation consists of a >300-m-thick, coarsening-upward succession of shallow-marine and terrigenous deposits that unconformably overlie the complexly deformed Romanzof chert of the Whale Mountain allochthon; however, this contact relationship is obscured

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**Figure 4. Cross section through the eastern half of the northeastern Brooks Range illustrating the major structural features and deformation trends with no vertical exaggeration (modified from Hanks, 1988; Wallace and Hanks, 1990; Moore, 1999).** Approximate location of the section is shown in Figure 2. Pre-Mississippian structural features are constrained by field data along the Kongakut River, Alaska. Depth of detachment in the pre-Mississippian units is adopted from Hanks (1989) and Peapples et al. (1997). WMT—Whale Mountain thrust.
by displacements along a major south-dipping Cenozoic thrust fault (the Aichilik Pass thrust of Anderson et al., 1994).

Deformation in the NE Brooks Range

The NE Brooks Range was affected by at least two major deformational events. Pre-Mississippian rocks throughout the NE Brooks Range are highly strained into tight, east-trending folds that display a combination of subhorizontal and steeply dipping penetrative fabrics (e.g., Oldow et al., 1987; Lane, 2007). The fabrics are not present in the Middle Devonian Utungrat formation, implying a regional pre–Middle Devonian phase of deformation (Anderson et al., 1994), now widely known as the Romanzof orogeny (Lane, 2007). The paleogeographic and tectonic setting of this pre–Middle Devonian deformation are not well constrained, although Lane (2007) inferred from field and subsurface data that deformation was localized along the ancestral margin of northwest Laurentia, where a continent-scaled terrane encroached from the north (present coordinates) and progressively accreted to the margin in the Early–Middle Devonian. It is critical that this assumes a fixed position of the North Slope with respect to northwest Laurentia throughout the Paleozoic.

The latest phase of deformation in the NE Brooks Range relates to the Late Jurassic (?) to Mississippian sequence and a roof thrust in the Miocene Brookian orogeny, which is considered the result of deformation in the NE Brooks Range (Fig. 4), we illustrate the Brookian style of deformation as a series of large imbricated fault-bend folds that culminate in a detachment between 8 and 15 km below the surface, which is derived from previous structural studies in the region (Hanks, 1989; Peapples et al., 1997; Cole et al., 1999; Moore, 1999; O’Sullivan and Wallace, 2002). The ramps of the fault-bend folds are often represented by major thrust faults that are as much as 100 km in length, including the Whale Mountain and Romanzof Mountain thrusts (WMT and RMT; Fig. 2). Apatite fission-track and 40Ar/39Ar thermochronological data indicate that many of these basement-involved thrusts underwent significant Cenozoic displacement (Hanks, 1993; O’Sullivan, 1994; Peapples et al., 1997; O’Sullivan and Wallace, 2002).

Differentiating between Brookian and Romanzof deformation fabrics in the NE Brooks Range represents a significant challenge to the understanding of the regional structural architecture. Most structural models collectively treat pre-Mississippian units as rigid thrust panels that undergo no internal shortening in response to Brookian contraction (Hanks, 1989; Wallace and Hanks, 1990; Cole et al., 1999; Moore, 1999; O’Sullivan and Wallace, 2002); however, these assumptions are oversimplified and problematic. For example, in the Mount Greenough antiform, the primary study area for this research, the classical north-directed fault-bend fold model (e.g., Wallace and Hanks, 1990; Moore, 1999) predicts that most of the structures and bedding planes should dip to the south (Fig. 4). In contrast, our field observations show that most of the pre-Mississippian units dip to the north, as illustrated in our schematic cross section along the Kongakut River (Fig. 4). These structural simplifications also fail to explain the structural relationship between rocks of the Whale Mountain allochthon and Clarence River group, which cannot be restored by simple line-length restorations of a single fault-bend fold as modeled by Moore (1999). Although these issues are largely beyond the scope of this contribution, we highlight important issues brought to light by our new geochronological data that will guide future structural studies in the region.

METHODS AND RESULTS

U-Pb Detrital Zircon Geochronology

We analyzed 11 samples of sandstone from the NE Brooks Range for U-Pb detrital zircon geochronology by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the University of California–Santa Cruz following the procedures outlined by Sharman et al. (2013). An additional sample (40LF13) was analyzed by combining LA-ICP-MS at Stockholm University with secondary ion mass spectrometry (SIMS) at the NordSIM facility at the Swedish Museum of Natural History following procedures outlined by Beranek et al. (2013a). The samples are separated into two distinct groups based on their major pre-Mississippian lithostatigraphic associations: (1) the Neoproterozoic–middle Cambrian Neroukup Formation (Leffingwell, 1919) and the Firth River group (Lane et al., 2016), and (2) the Lower Ordovician–Lower Devonian Clarence River group, including the Buckland Hills succession of Lane et al. (2016). The sample descriptions, raw geochronologic data, and procedures for collecting and interpreting the data are provided in the GSA Data Repository. The individual ages from each sample were filtered on the basis of concordance between 206Pb/238U ratios, U and Th concentrations, and degree of uncertainty in the calculated ages (for a detailed discussion, see Data Repository). These filtered subsets of the data are presented as stacked normalized age-probability plots (Figs. 5 and 6).

Neroukup Formation and Firth River Group

The majority of the Neroukup Formation samples were collected from a broad belt of predominantly north-dipping strata exposed within the core of the Mount Greenough antiform in the southern British Mountains (Fig. 2). These samples generally consist of coarse- to fine-grained, subrounded, quartz and sublithic arenites, with occasional feldspar, chert fragments, muscovite, and other accessory minerals. Most of these samples contain a complex assemblage of clay minerals that occupy interstitial space or compose the supporting matrix, and some samples have undergone intense deformation resulting in authigenic mica growth and pronounced strain shadows around individual quartz grains (Fig. DR1). Beds range between 0.5 and 2 m thick, are typically interbedded with intensely foliated green-gray argilite, and occasionally show flutes, scorches, and Bouma A–D cycles. Two additional samples were collected from within the Aichilik River antiform in the northern British Mountains (Fig. 2). One sample (12JT32) was collected from an outcrop of units lithologically similar to the Neroukup samples collected in the southern British Mountains and to those described by Lane et al. (2016) in the northern British Mountains of Yukon. Another sample (12JT31) was collected from the phyllite and quartzite of Old Gyngi Mountain (map unit pCpq of Reiser et al., 1980), which we assign to the Firth River group because of its inferred lower stratigraphic position with respect to the Neroukup Formation (Fig. 2). This sample was collected from an outcrop of subvertical, intensely foliated green-gray argilite and interbedded fine-grained quartzite, which is cut by numerous quartz veins that have undergone rotation from left-lateral, east-west shear.

Samples from the Neroukup Formation and Firth River group yield populations of well-rounded to elongate zircon. All seven samples show similar U-Pb age distributions with prominent Paleoproterozoic and Neoproterozoic age peaks that are between ca. 2000 and 1700 Ma, 2400 and 2200 Ma, and 2600 and 2400 Ma (Fig. 5). Meso- and Neoproterozoic zircons only constitute subordinate populations in most samples that range between ca. 1500 and 1100 Ma. The Firth River group sample (12JT31) is mostly indistinguishable.
from the other Neruokpuk samples, with a slightly more prominent population of Mesoproterozoic zircon grains ca. 1300 Ma. Sample 12JT10 is the only sample that contains young zircons, represented by two single-grain ages of 632 ± 29 Ma and 936 ± 43 Ma (2σ).

**Clarence River Group**

Sandstone samples from the Lower Ordovician–Lower Devonian (?) Clarence River group are texturally and compositionally immature. Individual sample descriptions and photomicrographs are provided in the Data Repository item. Four of the samples (12JT22, 12JT23, 12JT24, and 40LF13) were collected from outcrops along the northern edge of the Mount Greenough antiform (Figs. 2 and 4) in map units Cp and Cs of Reiser et al. (1980). Three of these samples (12JT22, 12JT24, and 40LF13) consist of medium- to fine-grained, angular quartz grains with occasional feldspar and coarse-grained detrital muscovite (Fig. DR2). These samples have an abundant (>25%) clay matrix, dominated by very fine mica, calcite, quartz, chlorite, and other clay minerals. Sample 12JT23 contains a variety of medium- to coarse-grained and angular clasts of monocrystalline and polycrystalline quartz, plagioclase feldspar, and chert, with minor volcanic and sedimentary lithic fragments, devitrified glass, and opaque minerals. The stratigraphic positions of each sample with respect to one another are uncertain, as the outcrops in this region are highly folded and possibly imbricated by minor thrust faults. Beds range between 0.1 and 0.3 m thick, are typically interbedded with micaceous black siltstone or shale, and characterized by Bouma A–D cycles.

A fifth sample (12JT35) was collected from a highly weathered outcrop of volcaniclastic and tuffaceous sandstone units in the northern British Mountains (map unit Ovc of Reiser et al., 1980), an area we refer to informally as the Caribou Pass antiform (Figs. 2 and 4). The sample contains medium- to fine-grained, subrounded to rounded opaque minerals, sericitized plagioclase, monocrystalline and polycrystalline quartz, volcanic rock fragments, and chert fragments in a clay-carbonate cement.

The distributions of U-Pb zircon ages among the Clarence River group samples are variable (Fig. 6). Sample 12JT22 is mostly composed of zircon older than 1000 Ma (~85%), with a broadly distributed population between ca. 2000 and 1300 Ma and a subordinate population between ca. 1200 and 1000 Ma. The younger population in this sample consists of three grains (~4%) that range between ca. 480 and 440 Ma and a second population of grains between ca. 990 and 800 Ma (~12%). Sample 12JT24 yields a small fraction of 25 zircon grains with age populations ranging between ca. 2000 and 1900 Ma (~57%) and 2700 and 2200 Ma (~43%). Zircon U-Pb ages from the lithic sandstone unit, sample 12JT23, comprise a nearly unimodal age population (~93%) between ca. 520 and 370 Ma (peak ca. 430 Ma; Fig. 6). This sample also contains two very small populations of older ages between ca. 650 and 560 Ma (~4%) and 2700 and 1150 Ma (3%). The volcaniclastic unit, sample 12JT35, also yields a unimodal age population between ca. 570 and 440 Ma (peak ca. 500 Ma, ~97% of grains; Fig. 6). Only two zircon grains yield ages outside of the main population: 620 ± 40 Ma and 1304 ± 44 Ma (2σ).

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**Figure 5.** Normalized probability density plots of U-Pb detrital zircon ages from the Neruokpuk Formation. Ratio of analyses plotted versus total zircon analyzed is shown in upper right along with the sample number (see Fig. 2 for sample location). All analyses were conducted by laser ablation–inductively coupled plasma–mass spectrometry at the University of California Santa Cruz. The raw data and filtering methods are reported in Table DR3.
Sample 40LF13 was analyzed by LA-ICP-MS at the Department of Geological Sciences at Stockholm University. Direct comparison of the zircon ages from this sample with other Clarence River group samples should be done with caution because the isotopic measurements were conducted on different instruments with different sets of zircon standards (see Data Repository). This sample yields three broad age populations between ca. 470 and 380 (~7%), 990 and 820 Ma (~40%), and 2000 and 1530 Ma (~53%). In addition to the LA-ICP-MS ages, 26 euhedral grains were selected and analyzed by SIMS. A filtered subset of 21 U-Pb ages is plotted along with the LA-ICP-MS data in Figure 6. The main age populations are between ca. 440 and 420 Ma (23%), 990 and 960 (23%), 1230 and 1000 (19%), 1510 and 1300 (14%), and 1726 and 1600 Ma (14%), with one Archean grain yielding a single-grain age of 2727 ± 5 Ma (1σ). The youngest single-grain age is 426 ± 3 Ma (1σ), and a cluster of four ages, which overlap in age at 1σ, yield a weighted mean age of 439 ± 3 Ma (1σ; Fig. 6). The ca. 1510–1000 Ma zircon ages observed in the SIMS distribution were filtered out from the LA-ICP-MS distribution because of substantial uncertainty (>10%) in the 206Pb/207Pb age, a typical phenomenon that occurs in LA-ICP-MS data sets at the crossover in precision between 206Pb/238U and 206Pb/207Pb ages caused by low intensity of the 207Pb signal.

40Ar/39Ar Muscovite Geochronology

Stepwise 40Ar/39Ar dating of single grains of muscovite from four samples from the Nenukpuk Formation and three samples from the Clarence River group was done at the University of Alaska Fairbanks following the procedures outlined by Martin et al. (2015). Step-heating experiments were conducted on one of the samples (12JT24) from an aggregate of very fine grained muscovite (i.e., whole-rock chip). In another sample (14BJ27), we combined stepwise techniques with single-grain fusion 40Ar/39Ar geochronology (K-Ar equivalent ages) on 14 individual grains to investigate intra-sample age variability. The samples collected for the 40Ar/39Ar analyses have undergone thermal conditions above the diagenetic zone (>200 °C) and are within the range of anchizone to epizone metamorphic grades. All samples contain populations of coarse muscovite grains that are typically ~250–1000 μm in length, as well as fine-grained packets of interstitial muscovite that are ~10–100 μm thick. The sampled muscovite grains are typically situated within thin (~50 μm) disjunctive cleavage domains that envelop lens-shaped domains of quartz and other framework minerals. In most cases, we targeted the coarse-grained fraction of
muscovite during the separation process. A summary of the $^{40}$Ar/$^{39}$Ar ages from each sample are presented in Table 1 and the step-heating results are illustrated in Figures 7 and 8. The complete geochronological data, procedural methods, sample preparation techniques, and detailed petrographic descriptions are provided in the Data Repository.

Results from the four Neruokpuk samples show complex and varied age spectra. Two of the samples (37LF13 and J1355–671) show significant scatter between heating steps, but most of the age steps from these samples are older than 800 Ma (Fig. 7A), indicating that the analyzed grains are clearly detrital. The other two samples (12JT12 and 12JT13b; Fig. 7B) are distinguished by having $^{40}$Ar/$^{39}$Ar ages that are apparently younger than the depositional age of the Neruokpuk Formation. Sample 12JT13a shows a plateau release at 404 ± 3 Ma (Fig. 5B; 69% cumulative $^{39}$Ar release). The stepwise results from sample 12JT12 show an irregular-shaped spectrum with 5 of the 12 steps (~77% cumulative $^{39}$Ar release) yielding ages between ca. 430 and 372 Ma, where two consecutive steps yield a weighted mean age of 430 ± 15 Ma (Fig. 7B; 51% cumulative $^{39}$Ar release).

Three of the four Clarence River group samples (09LF13, 40LF13, and 14BJ27) yield plateau release ages of 458 ± 3 Ma (97% of the $^{39}$Ar), 436 ± 1 Ma (~75% cumulative $^{39}$Ar release), and 473 ± 2 (~98% cumulative $^{39}$Ar release), respectively (Fig. 8). The step-heating results from whole-rock chip sample (12JT24) shows significant scatter between heating steps, with a plateau release age of 418 ± 7 Ma constructed from four consecutive steps between ca. 420 and 421 Ma (~40% cumulative $^{39}$Ar release) (Fig. 8). The $^{40}$Ar/$^{39}$Ar single-grain fusion experiments on sample 14BJ27 produced a range of ages from 521 ± 5 Ma to 441 ± 2 Ma (Fig. 9). From this sample, we calculated a weighted mean age of 473 ± 2 Ma from five overlapping ages generated by four single-grain fusion ages and the integrated age (fusion age equivalent) from the step-heating experiments (Table 1).

**DISCUSSION**

The presence of Ordovician, Silurian, and Devonian zircon and muscovite from map units that were originally assigned to the Cambrian and Ordovician (e.g., Reiser et al., 1980) requires a reassessment of NE Brooks Range stratigraphy. Challenges associated with stratigraphic correlation across the Alaska-Yukon border in the NE Brooks Range have persisted because fossil localities are sparse and structural complexities disrupt the lateral continuity of major map units (e.g., Lane, 1991). In the following we incorporate our new radiometric ages to make inferences about the structural and stratigraphic architecture of the NE Brooks Range and then place our findings within the context of the early Paleozoic tectonic evolution of northern Laurentia.

**Age and Provenance of the Neruokpuk Formation**

As highlighted herein, the depositional age and depositional environment of the Neruokpuk Formation are still not well understood. At the most fundamental level, the sedimentological, petrological, and provenance characteristics are typical of a passive margin setting (e.g., Leffingwell, 1919; Reed, 1968; Dutro et al., 1972;...
**Figure 7.** Stepwise 40Ar/39Ar age spectra of muscovite separates from the Neruokpuk Formation. (A) Samples that have retained detrital Ar (37LF13 and J1355–617). (B) Samples that have been partially or completely reset (12JT12 and 12JT13a). Analytical uncertainties are represented by vertical width of bars at the 1σ level. Steps filled in dark gray were used for plateau age determinations. Weighted mean plateau ages (WMPA) are calculated using at least three contiguous steps that overlap in error at 1σ, and compose more than 60% of the 39Ar release. Pseudo plateau ages (PPA) are calculated using the weighted mean age of two or more contiguous steps that overlap in error at 1σ, and compose 50%–60% of the 39Ar released. Analyses are reported in Table DR6.

**Figure 8.** Stepwise 40Ar/39Ar age spectra on muscovite separates from the Clarence River group. Analytical uncertainties are represented by vertical width of bars at the 1σ level. Steps filled in dark gray were used for plateau age determinations. Weighted mean plateau ages (WMPA) are calculated using at least three contiguous steps that overlap in error at 1σ, and compose more than 60% of the 39Ar release. Pseudo plateau ages (PPA) are calculated using the weighted mean age of two or more contiguous steps that overlap in error at 1σ, and compose 50%–60% of the 39Ar released. Analyses are reported in Table DR6.

**Figure 9.** Distribution of the single-grain 40Ar/39Ar total fusion and stepwise integrated ages from sample 14BJ27 (Clarence River group). Analytical uncertainties are represented by the vertical width of bars at the 1σ level. The five ages filled in dark gray, composed of four total fusion ages and one stepwise integrated age, were used for weighted (Wtd.) mean age calculation (MSWD—mean square of weighted deviates). Analyses are reported in Table DR7.
Lerand, 1973; Lane, 1991; Lane et al., 2016); however, the structural complexity and unfossiliferous nature of these units impedes our current understanding of basin architecture, regional stratigraphic relationships, and correlations with age-equivalent units across the northern margin of Laurentia.

In addition to the new detrital zircon ages presented herein, abundant detrital zircon data are now available from coeval Neoproterozoic–middle Cambrian units in the NE Brooks Range (Fig. 10; Macdonald et al., 2009; Strauss et al., 2013; McClelland et al., 2015; Lane et al., 2016). We have compiled these data into five composite detrital zircon suites that represent distinct geographical localities. Suite 1 is compiled from samples dated by Macdonald et al. (2009) and Strauss et al. (2013). These were collected from sedimentary units that are exposed below Neoproterozoic–Ordovician carbonate platform rocks of the northern Sadlerochit Mountains (Fig. 2), and are thus older than the Neruokpuk Formation and possibly correlative to the Firth River group on the basis of age. Suite 2 is compiled from samples dated by Strauss et al. (2013) and this study (12JT31), which includes the mixed carbonate and siliciclastic strata of the Firth River group exposed in the northern British Mountains of Alaska (Aichilik River antiform).

Suite 3 includes samples from the Neoproterozoic–middle Cambrian strata in the Barn Mountains of Yukon (McClelland et al., 2015), which are typically considered southeastern equivalents of the Neruokpuk Formation (e.g., Lane, 1991). Suite 4 represents the Neruokpuk Formation of the northern British Mountains, and is constructed from one sample dated by Strauss et al. (2013), three samples dated by Lane et al. (2016), and one sample from this study (12JT32). Suite 5 comprises the five samples dated in this study from the Neruokpuk Formation in the southern British Mountains of Alaska (Mount Greenough antiform).

The Neoproterozoic–middle Cambrian units as a whole contain populations of ca. 1200–1000, 1500–1300, 2000–1800, and 2800–2600 Ma zircon, but the relative abundances of individual populations, particularly the Mesoproterozoic populations, vary among the composite suites (Fig. 10). The zircon signatures from the Sadlerochit Mountains and the Firth River group have similar proportions of each of the major populations, but samples from the Sadlerochit Mountains contain a subpopulation of Neoproterozoic (ca. 980–760 Ma) grains that are not present in any of other composite suites of the NE Brooks Range. The composite Neruokpuk suite from the Barn Mountains also contains Mesoproterozoic populations, but these have slightly smaller proportions (Fig. 10B). The Neruokpuk units of the northern and southern British Mountains mostly lack the prominent Mesoproterozoic age populations and have nearly identical cumulative probability trends, indicating that detrital zircons from these two suites were likely shed from the same source region.

The proportional differences among the detrital zircon suites are likely an artifact of stratigraphic age. The samples from the northern Sadlerochit Mountains are stratigraphically below the ca. 720 Ma Kikikat volcanics (Cox et al., 2015) and contain zircon grains as young as ca. 760 Ma, indicating that these units were deposited in the middle Cryogenian (Macdonald et al., 2009; Strauss et al., 2013). The Firth River

Figure 10. U-Pb detrital zircon ages from Neoproterozoic–Cambrian units throughout the northeastern Brooks Range. (A) Compared using normalized probability density plots. (B) Compared using cumulative probability plots. Data are from (1) Macdonald et al. (2009); (2, 4, and 5) Strauss et al. (2013); (3) McClelland et al. (2015); (4) Lane et al. (2016); (2, 4, and 5) this study. Fm—formation; gp—group.
group samples are typically assumed to be older than the units from the Neruokpuk Formation (e.g., Dutro et al., 1972; Reiser et al., 1980; Lane et al., 2016) and are possibly correlative with the units in the northern Saddlerock Mountains (Macdonald et al., 2009; Strauss et al., 2013), indicating that they were likely deposited in the Cryogenian or Ediacaran. The abundant populations of Mesoproterozoic zircon in these composite suites may have been sourced by recycling distal deposits of the Grenville foreland basin that blanketed much of the Laurentian continent in the Neoproterozoic (Rainbird et al., 1992, 1996, 2012). The Neruokpuk units of the Arctic Islands (Anfinson et al., 2012; Hadlari et al., 2009), indicating that paleogeographic correlation of the Neruokpuk Formation, but also record a prominent shift in provenance. A useful application of detrital zircon data is the ability to constrain the maximum depositional age of strata (Dickinson and Gehrels, 2009), especially where biostatigraphic constraints are limited (e.g., Kochelek et al., 2011); however, utilizing robust maximum depositional ages from the LA-ICP-MS data presented herein for the Clarence River group is difficult because of the large uncertainty (~4.5%) on many of the individual ages. Furthermore, determining the degree of discordance for grains generally younger than 700 Ma is challenging due to large uncertainties in the $^{207}$Pb/$^{206}$Pb age, a common problem in most detrital zircon data sets (Nemchin and Cawood, 2005), and thus measurements compromised by Pb loss or inheritance cannot be ruled out. For these reasons, the most conservative estimate for the maximum depositional age from our LA-ICP-MS zircon ages is determined by using the center of the youngest graphical peak from the individual normalized probability distributions (Fig. 6).

The younger fractions released during the step-heating experiments may have also been influenced by partial degassing during Brodkian tectonic and/or burial events. This was highlighted in one Neruokpuk sample in the northern British Mountains (Lane et al., 2016), where Ar loss as young as ca. 150 Ma was ascribed to the Jurassic to middle Cretaceous rifting and sedimentation associated with the opening of the Canada Basin. Much of this region is considered to have been unaffected by rifting events (Moore et al., 1994), so an alternative hypothesis is that rocks of the NE Brooks Range were significantly buried by the Late Cretaceous to Cenozoic foredeposits of the Brodkian orogen. Color alteration of conodonts, vitrinite reflectance, and apatite fission track ages from Bathtub Ridge (Fig. 2) predict that the pre-Mississippian strata of the Mount Greenough antiform were buried below ~10 km of sediment before being exhumed in the middle Cenozoic (O’Sullivan, 1994; Bird et al., 1999; Moore, 1999); however, an additional 4–7 km of overburden is needed to reach the ~425–400 °C muscovite closure temperature (assuming a normal geothermal gradient of ~30 °C/km). Therefore, given the significant releases of $^{39}$Ar ca. 430 and 404 Ma, we ascribe most of the resetting and/or loss to a major Silurian–Early Devonian low-grade metamorphic event that occurred during the Romanzof orogeny.

### Age and Provenance of the Clarence River Group

As discussed here, the depositional age and stratigraphic architecture of the newly proposed Clarence River group remain unknown; however, it is clear from the regional stratigraphic architecture and from the U-Pb and $^{40}$Ar/$^{39}$Ar data that these units not only overlie the older Neruokpuk Formation, but also record a prominent shift in provenance. A useful application of detrital zircon data is the ability to constrain the maximum depositional age of strata (Dickinson and Gehrels, 2009), especially where biostatigraphic constraints are limited (e.g., Kochelek et al., 2011); however, utilizing robust maximum depositional ages from the LA-ICP-MS data presented herein for the Clarence River group is difficult because of the large uncertainty (~4.5%) on many of the individual ages. Furthermore, determining the degree of discordance for grains generally younger than 700 Ma is challenging due to large uncertainties in the $^{207}$Pb/$^{206}$Pb age, a common problem in most detrital zircon data sets (Nemchin and Cawood, 2005), and thus measurements compromised by Pb loss or inheritance cannot be ruled out. For these reasons, the most conservative estimate for the maximum depositional age from our LA-ICP-MS zircon ages is determined by using the center of the youngest graphical peak from the individual normalized probability distributions (Fig. 6).

Only one sample from the Clarence River group (12JT24) does not contain Paleozoic zircon, whereas the other four samples have maximum depositional peak ages that range between ca. 500 and 430 Ma (Fig. 6). Sample 12JT23 has the youngest graphical peak, ca. 430 Ma, and although this age is within the middle Wenlock (Gradstein et al., 2012), 19 single-grain
ages have normal distributions centered in the Devonian (assuming each zircon age has a normal distribution using the age as the mean and uncertainty as the standard deviation). Despite this, clear clustering of the Devonian grains is not observed in the normalized probability distribution plot and there is no apparent trend in their U concentrations or U/Th ratios, suggesting that they simply represent the youngest ages from a continuous distribution that results from analytical uncertainty or Pb loss. This is also supported in the age distribution of sample 40LF13, where we combined LA-ICP-MS and SIMS techniques. The four overlapping SIMS ages yield a weighted mean age of 439 ± 3 Ma (Fig. 6), which nearly corresponds with the ca. 440 center of the youngest graphical peak in LA-ICP-MS age distribution, supporting the notion that these peaks conservatively represent maximum depositional ages.

Sample 12JT35 was collected from map unit Ovc of Reiser et al. (1980) in the Caribous Pass antiform (Fig. 2) of the northern British Mountains, and has a maximum depositional age of ca. 500 Ma (Furongian). This closely corresponds with the approximate age of the trilobite fossils from the Whale Mountain volcanic rocks and associated limestones in the Mount Greenough antiform (Dutro et al., 1972); this might imply that these volcaniclastic rocks were sourced from Whale Mountain allochthon.

The composite detrital zircon signature of the Clarence River group (Fig. 11) implies derivation from several different source areas. The subordinate Archean–Paleoproterozoic populations were likely derived from crystalline basement rocks of Laurentian craton and may have been cycled through several sedimentary units prior to deposition. The early Neoproterozoic (ca. 990–820 Ma) age population of samples 12JT22 and 40LF13 is critical because original source regions within this age range are not widespread throughout Laurentia. Tonian magmatism is typically attributed to postorogenic collapse of the Grenville orogen, as recorded in the Central Gneiss Belt of Ontario, Canada (Ketchum et al., 1998), the East Greenland Caledonides (Kalsbeek et al. 2000; Watt et al., 2000), the Gros Morne Bay and Pinware terranes of eastern Labrador (Gower, 1996), and the Lewisian uplift in northwestern Scotland (Turnbull et al. 1996). Early Neoproterozoic magmatic rocks are also observed in the peri-Laurentian terranes of the northern Caledonides, including Pearya (e.g., Trettin, 1998) and the various terranes of Svalbard (e.g., Gee et al., 1995; Ohta et al., 2002; Johansson et al., 2004). These zircon grains may have also been recycled from older sedimentary units that contain prominent early Neoproterozoic populations, such as the

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Figure 11. U-Pb detrital zircon ages from early Paleozoic sedimentary successions of northern Laurentia and associated Caledonian terranes, including: (1) southwestern Svalbard (Gasser and Andresen, 2013); (2) northwestern Svalbard (Pettersson et al., 2010); (3) Pearya terrane (Hadlari et al., 2014); (4) Ellesmere Island (Beranek et al., 2015); (5) northeastern Brooks Range (this study); (6) Ellesmerian clastic wedge in the Canadian Arctic Islands (Anfinson et al., 2012); (7) Ellesmerian clastic wedge in Yukon (Beranek et al., 2010); and (8) Ellesmerian clastic wedge in east-central Alaska (Gehrels and Pecha, 2014).
late Neoproterozoic Succession II of Pearya (e.g., Malone et al., 2014) and the Eleonore Bay Supergroup of the East Greenland Caledonides (e.g., Watt, et al., 2000).

Zircon from the ca. 470–420 Ma age population in the Clarence River group may have been sourced from magmatic rocks emplaced during the Caledonian-Appalachian orogeny, as similar U-Pb zircon ages are reported from magmatic rocks in the East Greenland Caledonides (e.g., Watt et al., 2000; Kalsbeek et al., 2001, 2008; Rehnström, 2010), Pearya (Trettin, 1987; McClelland et al., 2012), Svalbard (e.g., Johanson et al., 2004; Pettersson et al., 2009), New England and western Newfoundland (e.g., van Staal and Barr, 2012, and references therein), and the northern British Isles (e.g., Oliver et al., 2008). Caledonian-age magmatism is also observed on various circum-Arctic terranes such as the Alexander terrane (Gehrels and Saleeby, 1987; Beranek et al., 2013b; White et al., 2016) and Klamath and Sierran terranes (Grove et al., 2008). Note that magmatic rocks of this age group are rare in Arctic Alaska, although dredged samples of orthogneiss from the Chukchi Borderland (Fig. 1) yield U-Pb ages of ca. 430 Ma (Brumley et al., 2015) and volcanic rocks exposed in the Doornerrak fenster of the central Brooks Range (Fig. 1B) have ages that range from ca. 470 to 370 Ma (Dutro et al., 1976). Because biot stratigraphic constraints are limited for the samples dated in this study, we cannot exclude the possibility that this age population was recycled from an older sedimentary source; however, the compositional and textural immaturities of the Clarence River group samples, especially the presence of volcanic rock fragments and euhedral feldspar grains, imply direct sourcing from primary volcanic material.

The 40Ar/39Ar muscovite ages from the Clarence River group overlap with the prominent ca. 470–420 Ma detrital zircon population. Like the muscovite extracted from the Nuerokpuk samples, we interpret the Clarence River group muscovite as detrital in origin because it is typically coarse grained, has a strong petrologic contrast with the surrounding clay matrix, and is commonly disaggregated into single sheets. Three of four samples analyzed yield robust weighted plateau ages (Fig. 8; Table 1) that reflect the highly retentive nature of coarse detrital grains. Therefore, we interpret these 40Ar/39Ar muscovite ages as records of the timing of cooling and/or crystallization of the respective source regions.

The 436 ± 1 Ma 40Ar/39Ar muscovite age of sample 40LF13 (Fig. 8) is within error of the 439 ± 3 Ma weighted-mean age calculated from the cluster of four U-Pb zircon ages (Fig. 6). Possible source regions for this detritus are nonexistent along the northwest margin of Laurentia, but are widely exposed in the East Greenland Caledonides, which host ca. 440–430 Ma muscovite-rich, postorogenic S-type granites (Kalsbeek et al., 2000). This, along with the textural and compositional immaturities of the samples, implies that the Clarence River group was deposited in proximity to the Caledonides during the collision between Baltica and Laurentia. The other plateau ages of ca. 473 and 458 Ma are significantly older than the S-type granites in the East Greenland Caledonides and were likely sourced from magmatic or metamorphic rocks that formed in the early phases of the Caledonian-Appalachian orogeny. A similar age distribution is recorded in southwestern Wales (UK), where detrital muscovite ages from the lower Silurian Old Red Sandstone record exhumation of the Northern and Central Highlands of Scotland during the Early–Middle Ordovician Grampian orogeny (Sherlock et al., 2002).

Unlike the other Clarence River group samples, sample 12JT24 has an irregular, staircase-shaped age spectrum (Fig. 8). The complex nature of this spectrum is likely a response to analyzing a fine aggregate of multiple grains in a single step-heating experiment (i.e., whole-rock analysis). The sample was most likely perturbed by a low-grade metamorphic event ca. 418 Ma, possibly in relation to the Romanzof orogeny. It is also possible that the sample contains newly formed (authigenic) muscovite that grew via the alteration of other fine-grained clay minerals like illite or kaolinite; this is a common process that occurs in the formation of low-grade metamorphic rocks (e.g., Hunziker et al., 1986; Verdel et al., 2012).

**Paleogeography of the North Slope**

The contact between the Nuerokpuk Formation and Clarence River group marks a major shift in the dispersal of sediment in northern Laurentia. We postulate that this fundamental shift in provenance is linked to the closure of the northern tract of the Iapetus Ocean and the onset of the Caledonian orogeny. In this scenario, detritus was funneled from uplifted source regions in the East Greenland Caledonides, Pearya, Svalbard, and other circum-Arctic terranes, and transported axially along the Franklinian margin before filling the pre-Mississippian basin of the North Slope (Fig. 12). A similar scenario is inferred from age-equivalent strata in the Clements Markham and Hazen fold belts.

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**Figure 12. Paleogeographic position of terranes and sediment dispersal pathways along northern Laurentia during deposition of the Clarence River group (see text for discussion). Reconstruction is based on Trettin (1987, 1998), Patchett et al. (1999), McClelland et al. (2012), Gasser and Andresen (2013), Pettersson et al. (2010), Colpron and Nelson (2011), Anfinson et al. (2012), and Beranek et al. (2015). NE—northeastern.**
of northern Ellesmere Island, which is supported by paleocurrent trends (Trettin, 1994, 1998), regional shifts in Nd isotopic values (Patchett et al., 1999), and detrital zircon studies (Anfinson et al., 2012; Hadlari et al., 2014; Beranek et al., 2015). Although the exact paleogeographic position of the North Slope with respect to northern Ellesmere Island and the Caledonian orogen is uncertain, the composite detrital zircon signature for the Clarence River group (Fig. 11) is remarkably similar to Silurian flysch deposits (e.g., Fire Bay, Lands Lokk, and Danish River formations) of Ellesmere Island (Beranek et al., 2015) and age-equivalent units in Pearya (Hadlari et al., 2014). In addition, the compositional and textural immaturity of the Clarence River group sandstone samples highlights proximity to the source region. These observations provide support for recent paleogeographic interpretations that restore the North Slope to northeast Laurentia in the early Paleozoic (e.g., Strauss et al., 2013; Malone et al., 2014; Cox et al., 2015).

An alternative scenario fixes the North Slope to northwest Laurentia throughout the Paleozoic (e.g., Lerand, 1973; Lane, 1991, 2007; Moore et al., 1994; Rainbird et al., 1996; Cecile et al., 1999; Lane et al., 2016). In this model, synorogenic detritus of the Clarence River group may have arrived by long-distance transport from the Caledonides or from the localized collision of an allochthonous terrane or terranes with the northwest Laurentian margin; the latter is the interpretation of Lane (2007) and Lane et al. (2016), who drew correlations between portions of the Clarence River group (i.e., the Buckland Hills succession) and the upper Devonian Imperial Formation of northern Yukon. The Imperial Formation was deposited in the Ellesmerian clastic wedge (Beranek et al., 2010; Lemieux et al., 2011), which blanketed much of the Canadian Arctic and northwest Laurentian margin during the Late Devonian and Early Mississippian. Although the Ellesmerian clastic wedge units are lithologically similar and have comparable detrital zircons (e.g., Beranek et al., 2010; Anfinson et al., 2012; Gehrels and Pecha, 2014) and muscovite ages (Powell and Schneider, 2013), the deposition of the Clarence River group predates Ellesmerian clastic wedge sedimentation, as it was deformed in the Early–Middle Devonian Romanzof event (Anderson et al., 1994; Lane, 2007; Lane et al., 2016). Furthermore, the Clarence River group is crosscut by regional Late Devonian plutonic rocks, which are thought to be a principal source of detritus in Ellesmerian Classic wedge units (Beranek et al., 2010; Anfinson et al., 2012).

Positioning the North Slope near northeast Laurentia in the Silurian–Early Devonian (Fig. 12) requires >1000 km of left-lateral displacement along the Franklinian margin of Arctic Canada prior to the Late Devonian–Early Mississippian to achieve a hypothesized pre–Canada Basin paleogeographic configuration (e.g., Gottlieb et al., 2014; Houseknecht and Connors, 2016). In this scenario, the Romanzof orogeny may represent a major transpressional event that occurred along strike with similar deformation associated with the docking of Pearya against the northeast margin of Laurentia (Trettin, 1998, and references therein). A strike-slip orogen along the northern margin of Laurentia in the early Paleozoic is favored by a number of paleogeographic models for the Arctic (e.g., Sweeney, 1982; Oldow et al., 1987; Colpron and Nelson, 2011), and previous studies in the NE Brooks Range have postulated strike-slip displacement along the Kaltag-Porcupine-Rapid fault array in severing stratigraphic ties between the NE Brooks Range and northwest Laurentia (Oldow et al., 1987; Norris, 1997; Strauss et al., 2013; von Gosen et al., 2015).

**Origin and Emplacement of the Whale Mountain Allochthon**

The basic premise of the Whale Mountain allochthon model is that a structural complex composed of massive basalt flows, radiolarian chert, and limestone was emplaced onto the pre-Mississippian sedimentary units of the North Slope in the form of a single thrust sheet. Although previously researchers have interpreted the volcanic rocks as being in stratigraphic continuity with the other pre-Mississippian units (e.g., Dutro et al., 1972; Reiser et al., 1980; Lane, 1991; Lane et al., 2016), we observed the Clarence River group positioned below the volcanic rocks in almost all cases throughout the NE Brooks Range, indicating a major disruption in the stratigraphic sequence.

In the Mount Greenough antiform (Fig. 2), the volcanic rocks are juxtaposed above Clarence River group units by a low-angle thrust fault that was folded into a synform (Fig. 4). The age of this structure is unknown; however, along strike the thrust appears to juxtapose the volcanic rocks with the Lisburne Group of the Ellesmerian sequence (Reiser et al., 1980), indicating that some amount of Brookian displacement has occurred along the fault. If all of the displacement was a result of Brookian contraction, then shortening estimates across the NE Brooks Range are significantly underestimated. For example, an additional duplex or thrust panel would be required to retrodeform the Mount Greenough fault-bend fold in the model of Moore (1999) because it does not address the stratigraphic disruption observed between the Clarence River group and the overlying Whale Mountain volcanic rocks. Alternatively, the emplacement of the Whale Mountain allochthon could have occurred in the Early–Middle Devonian Romanzof orogeny with subsequent reactivation during Brookian shortening. Lane (2007) interpreted the Romanzof orogen as a southward-verging (present coordinates) fold-thrust belt largely on the lack of deformation in the Yukon block further to the south. The northward dips of the structural fabrics and apparent south-directed imbrications of the stratigraphy across the Mount Greenough antiform (Fig. 4) both favor a south-vergent model. Conversely, the metamorphic gradient and the intensity of deformation appear to decrease in the northern British Mountains (Sable, 1977), and the pre-Mississippian deformation in the Aichilik River antiform appears to be north vergent along the Aichilk River (Hanks, 1989). These north to south discrepancies in structural style could be the result of the juxtaposition of different pre-Mississippian structural domains along east-west–trending strike-slip faults, supporting the notion that the Romanzof orogeny had a significant transpressional component. However, the relationships between the structural styles of the sedimentary units with those of the Whale Mountain allochthon are obscured by the strong contrast in mechanical competence of the rocks.

A multitude of paleogeographic scenarios are possible for emplacement of the Whale Mountain allochthon and the associated Romanzof orogeny. We postulate that it occurred (1) from the accretion of an outboard terrane, possibly the southern subterrane of Arctic Alaska, (2) as the North Slope translated along the northern margin of Laurentia, or (3) some combination of both. Nevertheless, several outstanding challenges to the allochthon model remain. First, the source of the thrust sheet is unknown, largely because the fault that separates Whale Mountain allochthon from the Clarence River group is kinematically unconstrained. We prefer a north-directed sense of emplacement that restores the allochthon along a south-dipping thrust sheet to the Romanzof Mountain thrust exposed at the headwaters of the Jago River (RMT; Fig. 2). A second challenge is that the tectonic and/or depositional setting of the Whale Mountain allochthon can be interpreted in several ways from the available data. The geochemical signatures of the volcanic rocks are indicative of derivation from sublithospheric mantle (Moore, 1987; Goodfellow et al., 1995), which is typical for most basalts erupted in oceanic settings (e.g., Pearce, 2008), but continental flood basalts also have similar geochemical signatures (e.g., McKenzie and Bickle, 1988; Gallagher and Hawkesworth, 1992). It is important that these volcanic rocks are intimately associated with thick packages of radiolarian chert, slate, and phyllite, and
occasional lithic wacke of the Romanzof chert (Moore and Churkin, 1984; Mull and Anderson, 1991); this lends support to a deep marine origin. The structural and stratigraphic relationships of the volcaniclastic rocks exposed in the northern British Mountains, where sample 12JT35 was collected, may contradict the allochthon model. Detailed mapping by Kelley et al. (1994) placed these volcaniclastic rocks in stratigraphic continuity with Clarence River group, and suggested correlation with Whale Mountain volcanic rocks in the Mount Greenough antiform. However, outcrop exposure in northern British Mountains is relatively poor, and a scenario where these volcaniclastic rocks were deposited by reworking the Whale Mountain volcanic rocks and then subsequently imbricated with the Clarence River group units should not be eliminated from possible interpretations.

The Whale Mountain volcanic rocks are comparable to the continental flood basalts of the Selwyn basin on the basis of age (Leslie, 2009; MacNaughton et al., 2016) and geochemistry (Goodfellow et al., 1995), and correlation between the two volcanic suites is a critical component in models that prefer a fixed position of the North Slope with respect to northwest Laurentia (e.g., Lane et al., 2016). An allochthonous relationship between the Whale Mountain volcanic rocks and the pre-Mississippian sedimentary rocks of the North Slope permits the hybridization of the various paleogeographic models. For example, the paleogeographic model favored in this study (Fig. 12), with the North Slope originating near northeast Laurentia and translating along the Franklinian margin, could suggest that the Whale Mountain volcanic rocks erupted into an oceanward extension of the Selwyn basin and were subsequently assembled with rest of the North Slope by strike-slip juxtapositioning. Alternatively, the rocks of the Whale Mountain allochthon could be correlative to similar-aged volcanic rocks at northern Ellesmere Island, implying that the emplacement could have happened closer to the main Caledonian collisional belt. Either interpretation is permissible if the allochthon model is considered.

CONCLUSIONS

The U-Pb and Ar/Ar isotopic analysis on detrital minerals from 18 samples of pre-Mississippian strata in the NE Brooks Range of Alaska provide new constraints on the structural and stratigraphic architecture of the Arctic Alaska terrane. Two major sedimentary successions are now recognized in the British and Romanzof Mountains of Alaska: a Neoproterozoic–Cambrian passive margin succession that includes the Firth River group and the Nenupuk Formation, and the newly identified Lower Ordovician–Lower Devonian Clarence River group. In addition to these sedimentary units, a late Cambrian–Ordovician structural complex composed of massive basalt flows, radiolarian chert, and limestone, herein named the Whale Mountain allochthon, is structurally juxtaposed with the underlying Clarence River group. When compared with the ages of igneous and metamorphic rocks in Laurentia and other circum-Arctic regions, the new detrital geochronological data presented herein shed light on the origin and dispersal of siliciclastic material along the northern margin of Laurentia throughout the Neoproterozoic and early Paleozoic. Specifically, detritus of Firth River group and Nenupuk Formation was ultimately derived from Archean and Paleoproterozoic basement rocks in Canadian shield and possibly older sedimentary units of the Grenville foreland basin. The Clarence River group was most likely sourced from igneous and metamorphic rocks of Caledonian orogenic belt of northeast Laurentia. The pre-Mississippian rocks of the NE Brooks Range were subsequently deformed and underwent low-grade metamorphism during the ill-defined Early–Middle Devonian Romanozof orogeny, which was closely associated with the emplacement of the Whale Mountain allochthon. How this event relates to the greater paleogeography of northern Laurentia and the circum-Arctic is unresolved, but future plate reconstructions should consider the possibility that the North Slope was positioned near northeast Laurentia during the closure of the Ipats Ocean and Caledonian-Appalachian orogeny.

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