Provenance, U-Pb detrital zircon geochronology, Hf isotopic analyses, and Cr-spinel geochemistry of the northeast Yukon Koyukuk Basin, AK: Implications for Alaska interior basin development and sedimentation

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Abstract

The Yukon Koyukuk Basin is a large depression that covers ~118,000 sq. km in western interior Alaska that is divided into two sub-basins by a volcanic arc assemblage.

Interpretations of the depositional setting of the northern Kobuk Koyukuk sub-basin vary from a syn-collisional forearc basin to a post-orogenic successor basin formed by lithospheric extension. New results from sandstones and conglomerates collected from the Kobuk Koyukuk sub-basin provide evidence for the timing of basin development, insight into the provenance of coarse siliciclastic sediments, and the nature of Cretaceous paleogeography and paleodrainage of Arctic Alaska.

Early sedimentary rocks of the Kobuk Koyukuk sub-basin contain abundant mafic- to ultramafic-rich volcanic and plutonic lithic fragments and mafic heavy minerals (e.g., spinel, clinopyroxene, and amphibole). They also contain abundant Middle Triassic to early Late Jurassic zircons (240-160 Ma; peak maximum ~200 Ma) that yield highly juvenile Hf isotopic compositions. Geochemistry of chromium spinels ($Cr\# = 0.17 - 0.86$) suggests crystallization in an immature arc setting that likely developed over MORB-type crust. These early sediments are sourced from the mafic and ultramafic rocks of the Angayucham terrane, which was once much more extensive. These results suggest that the Angayucham terrane consists of a obducted Middle Triassic to early Late Jurassic oceanic arc complex that is coeval with oceanic to continental margin mafic arc magmatism in the Canadian Cordillera.

Our generalized stratigraphy, along with U-Pb ages and Lu-Hf isotope of zircons from sedimentary rocks of the Kobuk Koyukuk sub-basin reflect the tectonic and/or erosional unroofing of the adjacent southern Brooks Range and Ruby terrane. U-Pb ages of detrital zircons collected from the lowest stratigraphic mafic- to ultramafic-rich sediments yield maximum depositional ages (107 Ma) that reflect initial erosion of the structurally highest Angayucham terrane and initiation of basin formation and deposition

initiated in the late Early Cretaceous. Continued uplift and erosion exposed structurally deeper metamorphic rocks, as revealed by incorporation of low-grade phyllites and eventually higher-grade metamorphic schistose lithic detritus and intermediate composition (e.g. biotite) to metamorphic (e.g. chloritoid and xenotime) heavy mineral suites into the basin sediments. Differences in detrital zircon signatures between similar age strata in the Colville foreland basin to the north of the Brooks Range and the Kobuk Koyukuk sub-basin indicate that the sediments within the two basins were derived from two different sources and the Brooks Range orogen acted as a drainage divide during late Early Cretaceous deposition.

Introduction

Sedimentary basins that flank orogenic belts serve as archives that record the long-term deformational and uplift history of orogenic systems. When associated with a topographic effect, the kinematic evolution of an orogen affects the geometry, filling pattern, and provenance signature of the adjacent synorogenic sedimentary basins (Bayona, et al., 2008). Processes such as tectonic uplift and surficial denudation, rainfall, sediment supply, sediment transport and dispersal have direct implications on the evolution of synorogenic sediment routing systems (Whitchurch et al., 2011). As observed in several Cenozoic orogenic belts (e.g. Himalayas and Andes), differences in sedimentary filling patterns are recognizable by variations in large-scale axial and transverse river systems and smaller transverse rivers observed draining into and within the foreland and hinterland basins separated by an orogenic high (Burbank et al., 1996; Clark et al., 2004; DeCelles, 2012; Dietze et al., 2014; Hessler and Fildani, 2015). This

variation in drainage systems leads to differences in provenance signatures recorded within the basin sediments (Lease et al., 2007; Bayona, et al., 2008; Cina, et al., 2009; DeCelles et al., 2014). Therefore, the provenance signature of the sediments that occupy these basins should help in understanding the evolution of the synorogenic sediment routing systems on either side of the orogen.

In northern Alaska, the latest Jurassic – Early Cretaceous Brooks Range orogen is flanked by two synorogenic sedimentary basins, the northern Colville foreland basin and southern Yukon Koyukuk Basin (Fig. 1). Renewed deposition of thick successions of clastic rocks in the Colville Basin occurred coincidently with the formation of Yukon Koyukuk Basin, which led authors to conclude that these events were the result of orogenic uplift of the Brooks Range (Molenaar et al., 1984, 1986; Miller and Hudson, 1991; Till, 1992). Seismic reflection data collected within the Colville Basin delineate a series of turbidite-dominated sedimentary packages that longitudinally filled the basin from west to northeast from the late Early Cretaceous to the Cenozoic (Houseknecht et al., 2009; Houseknecht and Wartes, 2013). Despite all the work performed in characterizing the clastic rocks of the Colville Basin, little emphasis has been paid to understanding the formation and sedimentary evolution of the southern Yukon Koyukuk Basin.

The Yukon Koyukuk Basin is a large wedge-shaped physiographic depression, underlain by volcanic and marine sedimentary rock units, that covers ~118,000 sq. km (Fig. 1). Regional tectonic interpretations of the basin have been influenced by the occurrence of arc-affinity volcanic rocks that form the base of the Yukon Koyukuk sedimentary succession within the interior of the Yukon-Koyukuk Basin (Figs. 1 and 2)

(Patton and Box, 1989). Tectonic interpretations of the observed distribution of rocks across the basin vary widely, from the Yukon-Koyukuk province representing a basin formed in a syn-collisional forearc setting (Till et al., 1993) to its formation during post-accretion lithospheric extension of the hinterland (Miller and Hudson, 1991). The driving force for these interpretations is a disagreement on the duration of convergent deformation in the Brooks Range and the tectonic setting in which Early Cretaceous arc sequences were deposited in the early stages of the development of the Yukon Koyukuk Basin. Proponents for the forearc model propose that these volcanic units were deposited coincident with convergence and crustal thickening in the northern Brooks Range (Box, 1985; Till et al., 1993). Advocates for the lithospheric extension model suggest that the timing of volcanism is too young to be related to early thrust faulting in the Brooks Range.

The aim of this study is to: (1) evaluate the age, provenance, and geochemical nature of the sedimentary rocks in the northeast Yukon Koyukuk Basin; (2) establish their relationship to potential source terranes exposed in the surrounding Cretaceous metamorphic orogenic highlands that rim the basin; and (3) compare these new results to provenance signatures of the Colville basin to understand the Cretaceous paleodrainage adjacent to the active Brooks Range highland. To help answer these questions, we analyzed sediments for compositional variation and nature of heavy minerals suites, chemistry of chrome spinel, as well as U-Pb geochronology and Hf isotopic composition of detrital zircons and neighboring granitic plutons.

Geologic Setting

The Early to Late Cretaceous Yukon Koyukuk Basin is one of several Cretaceous basinal terranes that underlie interior Alaska. In south-central Alaska, these basinal terranes are characterized by thick sequences of marine volcanoclastic sandstone and mudstone, locally overlain by marine shelf sandstones and shales with thick coal-bearing sequences (Fig. 1; Kirschner, 1994). In north-central Alaska, the Yukon Koyukuk Basin consists largely of sandstones derived from mafic volcanic-plutonic sources followed by deposition of thick sections of clastic strata derived from the metamorphic rocks of continental-margin affinity (Patton and Miller, 1973; Patton et al., 1994, 2009; Nilsen, 1989; Dillon and Smiley, 1984).

The Yukon Koyukuk Basin is bordered on three sides by highlands that consist of metamorphosed and deformed Proterozoic to Mesozoic continental margin rocks and allochthonous oceanic assemblages of the Brooks Range (north), Seward Peninsula (west) and Ruby terrane (southeast) and Cretaceous plutons that intrude the metamorphosed rocks on Seward Peninsula and the Ruby terrane (Figs. 1 and 2). The oldest units at the base of the sedimentary succession are Cretaceous volcanic rocks, widely exposed in the center of the basin (Figs 1 and 2). These Early Cretaceous [K-Ar and paleontological ages summarized in Box and Patton (1989)] volcanic sequences range from mafic to intermediate in composition and were deposited in non-marine to deep-marine environments (Patton and Miller, 1966; Patton and Moll, 1985; Patton et al., 1978; Box and Patton, 1989). The overlying sedimentary deposits of the Yukon Koyukuk Basin are Early Cretaceous marine turbidites and late Early Cretaceous to Late Cretaceous sandstones and conglomerates (Fig. 2; Patton, 1973; Patton et al., 1994;

Patton et al., 2009; Dillon, 1989; Nilsen, 1989).

Because mafic and ultramafic assemblages of the Angayucham terrane (Moore et al. 1994) rim the margin of the Yukon Koyukuk Basin, Patton et al. (1977) suggested that the basin is underlain by oceanic crust. Although the nature of the crust beneath the eastern Yukon Koyukuk Basin is unknown, Late Cretaceous and Paleogene volcanic and plutonic rocks exposed in the western portion of the Yukon Koyukuk basin reflect melting of oceanic and/or island arc basalts with little to no isotopic evidence for the incorporation of older continental crust (Moll-Stalcup and Arth, 1989). This interpretation is supported by deep crustal seismic reflection profiling and modeling of gravity data that suggest the crust beneath the Yukon Koyukuk Basin is relatively thin (~32-35 km) (Cady, 1989; Fuis et al., 1997; Fuis et al., 2008).

Cretaceous sedimentary deposits

The lack of clearly defined lithostratigraphic marker units, poor fossil control, extremely poor exposures, and widespread regional folding have hindered development of a detailed regional stratigraphic framework for the Yukon Koyukuk Basin. However, a generalized stratigraphy has been established based on mapping, sampling and observations (Patton, 1973). Sedimentary deposits within the basin define two major regions of exposure (Fig. 2) referred to as the Lower Yukon sub-basin and the Kobuk Koyukuk sub-basin, separated by exposures of a volcanic arc assemblage located in the center of the basin (Fig. 2). Samples for this study were collected from the northeastern Kobuk-Koyukuk sub-basin region (Fig. 3; Supplemental Table 1).

161 The stratigraphic sequence of the Kobuk Koyukuk sub-basin generally consists of
 162 mid to Upper Cretaceous marine conglomerate, sandstone, and mudstone successions
 163 deposited by gravity flow mechanisms overlain by fluvial to shallow marine
 164 conglomerate, sandstone and shale (Fig. 3; Nilsen, 1989; Patton et al., 1994). The
 165 stratigraphically lower gravity flow deposits are exposed over the majority of the Kobuk
 166 Koyukuk sub-basin (unit Kvg of Patton et al., 2009; Figs. 2 and 3). Sandstone
 167 compositions are dominated by mafic volcanic lithic fragments, and are interpreted as
 168 being derived from the Angayucham terrane that rims the basin (Patton and Box, 1989)
 169 (Fig. 2). In the Kobuk Koyukuk sub-basin, conglomerates of this lower sedimentary unit
 170 have been dated as late Early Cretaceous (Albian) based on ammonoids and bivalves, and
 171 are composed of a variety of clast types that include mostly mafic igneous rocks and
 172 chert (Patton, 1973; Nilsen, 1989). The lower volcanic lithic sandstone and mudstone
 173 turbidite deposits are reported as being overlain by fluvial and shallow marine
 174 conglomerate, sandstone, and shale composed of (1) marginal conglomeratic deposits that
 175 rim the basin and (2) deltaic deposits that extend from the southeast margin across the
 176 southeastern part of the Kobuk-Koyukuk sub-basin (Kmc and Kqc map units of Patton et
 177 al., 2009; Figs. 2 and 3) (Patton, 1973; Dillon, 1989; Nilsen, 1989). Compositionally,
 178 these strata consist almost entirely of metamorphic detritus, and thus are interpreted to
 179 represent a younger part of the succession that overlies the Kvg strata with mafic volcanic
 180 sources (Dillon and Smiley, 1984; Patton and Box, 1989). The metamorphic detritus-rich
 181 conglomeratic section is dated as latest Early to Late Cretaceous (Albian to Santonian;
 182 Patton, 1973; Dillon and Smiley, 1984; Dillon, 1989). Patton and Miller (1968) report a
 183 K-Ar age of 83.4 ± 2.2 Ma (recalculated to ~ 86 Ma; Nilsen, 1989) for an ash-fall tuff

interbedded in this stratigraphically higher conglomerate unit exposed on the western flank of the Yukon Koyukuk Basin. All strata within the Kobuk Koyukuk sub-basin have been folded and faulted indicating regional shortening that is Santonian – Maastrichtian in age (Cushing and Gardner, 1987; Patton et al., 2009).

Exposures of Middle Jurassic to Early Cretaceous plutonic and volcanic rocks in the central part of the Yukon Koyukuk Basin are referred to as the Koyukuk terrane (Fig. 2). The Koyukuk terrane is characterized by a thick sequence of mafic to intermediate volcanic, volcanoclastic, and minor intrusive rocks. Based on the work of Patton (1973), Patton and Box (1989) and Box and Patton (1989), volcanic and intrusive rocks at the base of the Koyukuk terrane have the geochemical signature of volcanic arc magmas. The magmatic arc signature of the volcanic rocks together with their association upwards in the stratigraphic section with marine siliciclastic strata led Box and Patton (1989) to suggest that the Koyukuk terrane represents a submerged volcanic arc. It consists of two primary rock units: (1) Late Jurassic(?) and Early Cretaceous (Berriasian and Valanginian) mafic to intermediate volcanic flows and volcanoclastic rocks, and (2) middle to late Early Cretaceous (Hauterivian to Aptian) mafic to intermediate volcanic and volcanoclastic rocks. Igneous rock units of the Koyukuk terrane are then overlain by the late Early Cretaceous (Albian) clastic sediments (Patton and Box, 1989). These limited exposures of mafic crustal rocks and intermediate to felsic plutonic rocks are interpreted by Box and Patton (1989) to represent the basement of the Yukon Koyukuk Basin. All rock units of the Koyukuk terrane are intruded by a series of late Early to early Late Cretaceous intermediate to felsic plutons (118-78 Ma; K-Ar age; Fig. 2).

207 *Geology of source areas for sediments of the Yukon Koyukuk Basin*

208 Brooks Range

209 The Brooks Range orogeny initiated with Late Jurassic north-directed thrust
210 emplacement of the highest allochthons of the Angayucham terrane in an accretionary
211 prism setting (Roeder and Mull, 1978; Moore et al., 2015). This was followed by Early
212 Cretaceous northward thrust imbrication of the south-facing continental margin of Arctic
213 Alaska, which gave rise to the Brookian fold and thrust belt (Mayfield et al., 1988; Moore
214 et al., 2015 and references therein).

215 In the western Brooks Range, the northern part of the orogen is composed of a
216 series of stratigraphically thin allochthonous thrust sheets of Upper Devonian to Jurassic
217 marine continental margin sediments, each depositionally overlain by synorogenic deep-
218 marine clastic deposits (Mayfield et al., 1988). The Endicott Mountains allochthon is the
219 structurally lowest of seven major allochthons (Mayfield et al., 1988), and is composed of
220 a thick sequence of thrust-imbricated Late Devonian to Early Cretaceous shelf to basinal
221 sediments that range from non-metamorphosed to lower greenschist facies (Moore et al.,
222 1994). The Picnic Creek, Kelly River, Iqnavik River and Nuka Ridge allochthons
223 (bottom to top) structurally overlie the Endicott Mountains allochthon, and are composed
224 of late Paleozoic to early Mesozoic distal continental shelf strata, Mississippian to
225 Pennsylvanian carbonate platform deposits (only Kelly River and Nuka Ridge
226 allochthons) and Permian to Triassic fluvial to continental margin deposits (Moore et al.
227 2015 and references therein). The Copter Peak and Misheguk Mountain allochthons
228 (bottom to top) are the highest structurally in the Brooks Range, and together constitute
229 the Angayucham terrane. The Copter Peak allochthon consists of an imbricate stack of

230 fault slabs composed of pillow basalt, diabase, basaltic tuff, argillite, limestone and
 231 radiolarian chert metamorphosed to prehnite-pumpellyite or greenschist facies (~4 km
 232 total structural thickness; Gottschalk and Oldow, 1988; Dillon, 1989; Pallister et al.,
 233 1989; Moore et al., 2015). Overlying this package of rocks is the structurally highest
 234 Misheguk Mountain allochthon, which consists of ultramafic tectonite, ultramafic
 235 cumulates, gabbro, and diabase (total structural thickness ~3 km; Moore et al., 2015).
 236 The ultramafic rocks consist largely of dunite with chromitite layers and subordinate
 237 harzburgite, wehrlite, and pyroxenite (Zimmerman and Soustek, 1979; Bird et al., 1985).
 238 These ultramafic rocks are interlayered with, and transition upward into, layered
 239 cumulate gabbroic rocks, including troctolite, metagabbro, leucogabbro, and anorthosite
 240 (Zimmerman and Soustek, 1979; Nelson and Nelson, 1982; Bird et al., 1985). The basal
 241 contact of the Misheguk Mountain allochthon with Copter Peak allochthon is defined by
 242 a region of high-T contact metamorphism (i.e. an inverted metamorphic gradient or
 243 metamorphic sole) with $^{40}\text{Ar}/^{39}\text{Ar}$ ages of ~165-170 Ma (Wirth and Bird, 1992; Harris,
 244 1998).

245 Due to younger structural events, the basal detachment of the Endicott Mountains
 246 allochthon is now north-dipping (Moore et al., 1994 and references therein), and to the
 247 south lie exposures of rocks of the Central Belt which occur in its footwall. The Central
 248 Belt consists of structurally imbricated greenschist facies (locally HP/LT blueschist and
 249 amphibolite facies) metasedimentary and metavolcanic rocks of probable Late
 250 Proterozoic to Paleozoic age (Jones et al., 1987; Till and Snee, 1995; Till et al., 2008;
 251 Hoiland et al., *in press*). Lithologies include marble, calcareous-, chloritic- and pelitic-
 252 schist, scattered orthogneiss bodies, greenstone, and amphibolite. The early

Neoproterozoic Ernie Lake orthogneiss (968 ± 5 Ma; Amato et al., 2014) and Late Devonian Igikpak and Arrigetch Peak orthogneiss bodies within the Central Belt are variably deformed and metamorphosed (Nelson and Grybeck, 1980; Newberry et al., 1986; Patrick et al., 1994; Patrick, 1995; Toro et al., 2002). The Schist Belt lies south of the Central Belt, and is composed of polydeformed greenschist to epidote-amphibolite facies metasedimentary and metavolcanic units whose metamorphism overprints an earlier high-pressure/low-temperature event (HP/LT epidote-blueschist facies) (Till et al., 1988; Patrick et al., 1994; Patrick, 1995; Gottschalk, 1998). Early HP/LT metamorphism within the Central and Schist belts is thought to have occurred during subduction of the paleo-continental margin beneath an accreted island arc (Till, 1992; Moore et al., 1994). Flanking the Schist Belt to the south is the Phyllite Belt, a narrow belt of weakly metamorphosed and moderately deformed phyllites and metasandstones with local zones of phyllonite and chloritic schist *mélange* (Moore et al., 1994; Till et al., 2008). Metasedimentary strata of the Phyllite Belt are thought to be Devonian in age based on rare fossils (Gottschalk, 1987; Murphy and Patton, 1988).

The southernmost unit in the Brooks Range consists of tectonic slices of fault-imbricated mafic and ultramafic rocks and ocean floor sediments of the Angayucham terrane (Roeder and Mull, 1978; Pallister et al., 1989; Moore et al., 1994; Harris, 1995) that are virtually unmetamorphosed, and have been characterized in detail by Pallister et al. (1989). Here the Angayucham terrane is less than 5-10 km thick (structural thickness) and consists largely of Devonian to Jurassic age mafic-to-ultramafic rocks units and siliceous pelagic sediments (radiolarian chert) (Pallister et al., 1989). Geochemical data from the volcanic rocks of the Angayucham terrane show that many are hypersthene-

normative tholeiitic basalts (Barker et al., 1988; Pallister et al., 1989) and are transitional between normal and enriched mid-ocean ridge basalts (MORB) (Harris, 1995). Rare earth element (REE) patterns vary from relatively flat to slightly depleted or moderately enriched in light REE (LREE). Barker et al. (1988) and Pallister et al. (1989) interpreted the geochemical data as evidence for eruption of the basaltic rocks in oceanic plateaus such as seamounts and oceanic islands. However, based on crystallization sequences and mineral chemistries of rocks in the Misheguk Mountain allochthon, Harris (1995) suggested that crystallization occurred in an arc, rather than an oceanic plateau or seamount setting.

Exposures of the Angayucham units (Misheguk Mountain and Copter Peak allochthons) described above occur along a narrow zone that extends along the southern margin of the Brooks Range (Figs. 1, 2). These units have been interpreted as fault slivers of the highest structural allochthons in the Brooks Range, repeated and juxtaposed against metamorphic rocks by motion along down-to-the-south normal faults (Miller and Hudson, 1991; Christiansen and Snee, 1994; Moore et al., 1994; Little et al., 1994).

Ruby Terrane

To the southeast of the Yukon Koyukuk Basin, the Ruby terrane is a large region of metamorphic rocks trend NE-SW across the interior of Alaska (Fig. 1). The metamorphic rocks of the Ruby terrane consist primarily of Proterozoic(?) to Paleozoic metasedimentary rocks and minor metabasite and quartzofeldspathic gneiss (Dover, 1994; Moore and Box, 2016). Thermobarometry by Roeske et al. (1995) identified an Early Cretaceous, epidote blueschist metamorphism (10-13 kbar and 425-550°C) that is

overprinted by greenschist facies assemblages. In the western Kokrines Hills portion of the Ruby terrane, metamorphic assemblages document a later upper amphibolite to lower granulite facies event that likely overprinted the earlier HP metamorphic fabric in the late Early Cretaceous (~110 Ma; Roeske et al., 1995). These HP and HT metamorphic suites are structurally overlain in fault contact by Devonian slates and phyllites of the slate and phyllite belt and in turn structurally overlain by fault-bound slivers of the Devonian to Jurassic oceanic assemblage rocks of the Angayucham terrane, similar to mapped relations along the south side of the Brooks Range (Patton and Box, 1989; Dover, 1994; Moore and Box, 2016). All units are intruded by late Early Cretaceous (118-109 Ma; Patton et al., 1987; Roeske et al., 1998) granite and granodiorites. The plutons are chiefly composed of coarse-grained, K-feldspar-porphyritic biotite granite. The age of the Ruby batholith is determined by several methods (e.g., U-Pb, Rb-Sr and K-Ar), with ages that scatter from about 118 to 98 Ma (Blum et al., 1987; Patton et al., 1987; Miller, 1989; Roeske et al., 1995). Sr and Nd whole rock values reported by Arth et al. (1989b) suggest crustal involvement in the magmas. Isotopic values from the southwest plutons have slightly more radiogenic Sr and less radiogenic Nd compositions, characteristic of a relatively old continental source. Northeastern plutons of the Ruby Batholith have more radiogenic Nd relatively, characteristic of magma contaminated by smaller proportions of older continental crust (Arth et al., 1989b).

Methods

Sandstone composition

Petrographic and compositional data were obtained for 12 sandstones collected from the Kobuk Koyukuk sub-basin in the northeastern portion of the Yukon Koyukuk province (Fig. 3). Due to diagenetic alteration, not all samples were point-counted. Thin sections were analyzed according to the modified Gazzi-Dickinson point-counting method (Dickinson, 1970; Ingersoll et al., 1984). Modal compositions were determined by identifying 300 grains from each thin section. Calculated point-counting results are presented in Table 1, and based on procedures defined by Ingersoll et al. (1984) and Dickinson (1985).

Heavy mineral analyses

Following standard zircon separation techniques (crushing and grinding, water table, and magnetic and heavy liquid separation) to isolate zircon for U-Pb and Lu-Hf isotopic analyses, the remaining portion of heavy minerals were re-combined, sieved to 64-125 μm , density separated ($> 2.90 \text{ g/cm}^3$), and ‘dump’ mounted into a 1 x 1 cm square in epoxy resin and then polished. After mounting in epoxy, elemental and mineral proportions were obtained by element and phase mapping using an Oxford EDS detector attached to a Tescan VEGA3 SEM housed at the U.S. Geological Survey in Menlo Park, California. Twenty (1-mm field of view) images of each sample were captured and processed using the AZtec software. Proportions of the mineral phases were determined by taking the sum of the total area of each phase for all images collected for that sample. All tallied data are available in Table 2 and raw data are available in Supplementary

Table 2. Chromium spinel major- and trace-element geochemistry was obtained using the same Oxford EDS detector (Supplementary Table 3).

U-Pb geochronology

Zircons from 20 sedimentary and six igneous samples were mounted in epoxy resin and then polished to expose the grain centers. Cathodoluminescence (CL) images were collected using a Tescan Vega3 SEM at the U.S. Geological Survey in Menlo Park, California, to guide spot selection for isotopic analyses. The conditions for CL imaging were 10 kV and 16 nA.

U-Pb geochronology of detrital and igneous zircons was performed by laser ablation using the inductively coupled plasma mass spectrometer (ICP-MS) at the University of California, Santa Cruz. Data were collected using a single-collector Element XR high-resolution magnetic-sector ICPMS and a Photon Machines Analyte.H 193 ArF excimer laser equipped with a Helex 2-volume laser ablation cell. Mounted with the zircon separates, the Temora zircon (416.8 ± 1.1 ; Black et al., 2003) was used as a primary standard and FZ, Madder and Mount Dromidary were used as secondary standards and monitors. A 26 μm spot diameter was used for all analyses with a ATLEX 300i laser stabilized at 4.5 mJ.

For detrital zircons, around 100 spots on individual grains were analyzed per sample. Following the procedures of Sharman et al. (2013), all U-Pb data (detrital and igneous zircons) were reduced using Iolite (v. 2.2; Paton et al., 2010) and UPbGeochron3 add-ons for Igor Pro.

The results for detrital zircons were filtered to exclude ambiguous analyses based on the following criteria: discordance ($>20\%$), reverse discordance ($>5\%$), common ^{204}Pb content (>400 cps), and age precision ($>15\%$). To circumvent the possibility of xenocrystic zircons and calculate more precise magmatic ages, results obtained from conglomerate clasts and granitic intrusive rocks of the Ruby Batholith were filtered using the following criteria: discordance ($>5\%$), reverse discordance ($>2\%$), common ^{204}Pb content (>400 cps), and age precision ($>10\%$). U-Pb geochronology results are presented in Supplementary Tables 4 – 6. Weighted mean ages for conglomerate clasts and granite intrusions were calculated using Isoplot 3.7 (Ludwig, 2008).

Lu-Hf Analysis

Zircon Lu-Hf isotopic analyses were performed by laser ablation at the ICP-MS at Washington State University (WSU) using the methods described in Fisher et al. (2014), with the exception that U-Pb was not simultaneously determined. Laser spot analyses of zircon were placed directly on top of previous U-Pb ablation pits, using a NewWave 213 nm Nd:YAG laser with a laser spot diameter of $40\text{ }\mu\text{m}$. The laser was operated at 10 Hz with a fluence of $\sim 8\text{ J/cm}^2$. Lu-Hf isotopic measurements were performed on a ThermoScientific Neptune MC-ICPMS. In order to facilitate data collection, the Lu-Hf isotopic data are collected in a continuous, single data file that encompasses ~ 15 individual ablation analyses (each file consisting of up to 2400 individual 1 s integrations). The zircon standards FC1, GJ-1, Plesovice, R33 and a doped synthetic standard produced by Fisher et al. (2011) were used to monitor accuracy, including the pervasive interference of ^{176}Lu and ^{176}Yb on ^{177}Hf .

Results

Based upon field and petrographic observations, combined with quantitative compositional and heavy mineral results, deposits of the Kobuk Koyukuk sub-basin portion of the Yukon Koyukuk province were divided into three basic sedimentary types. Diagnostic characteristics of each sediment type are listed in table 3.

Type 1

Petrographic observations of thin-sections of Type 1 samples show them to be medium- to coarse-grained lithic-rich sandstones that show varying degrees of diagenesis (Fig. 4). Clasts in conglomerates interbedded with Type 1 sandstones are primarily chert, gabbro, low-grade quartzite, phyllite and vein quartz. Coarse-grained sandstones predominantly consist of lithic fragments, which include chert (Fig. 4A), volcanic rocks (mostly basaltic andesite in composition; Fig. 4B), mafic shallow intrusive and gabbroic rocks (Fig. 4C), and low-grade quartzite and phyllite (Fig. 4D). Minimally altered monocrystalline grains consist of plagioclase (Ca-rich; Fig. 4A), amphiboles, and clinopyroxene. The sandstone matrix is primarily composed of calcite (Fig. 4B), but small amounts of diagenic chlorite are also present (Fig. 4A). Epidote is observed as single grains, alteration products, and as clusters of crystals between lithic fragments, suggesting that epidote is a product of diagenesis (Fig. 4C).

Modal composition data for four samples of Type 1 sediments include predominantly lithic fragments (L) with varying subordinate amounts of plagioclase feldspar (F) and quartz (Q) (Table 1; Fig. 5). The total quartz composition consists

primarily of chert with minor amounts of monocrystalline quartz (Qm; Table 1 and Fig. 5). Only Ca-rich plagioclase feldspar (Ca-rich) is observed in the Type 1 sediments. Lithic fragments consist primarily of volcanic rock types (Lv) with sedimentary (Ls) and low-grade metasedimentary (LI) making up a relatively smaller overall percentage of the lithic fragments (Table 1; Fig. 5). When results are plotted on QFL diagrams, the modal composition of Type 1 sandstones falls within “magmatic arc” and “recycled orogen” provenance fields (Fig. 5). Quantitative mineral abundances (relative proportion of total area of grain mounts) of heavy mineral separates from Type 1 sediments reveal that these samples are composed primarily of mafic heavy minerals (e.g., sphene, clinopyroxene and Cr-spinel; Fig. 6). Sphene (i.e. titanite) is the most abundant heavy mineral observed in the Type 1 sediments, composing ~45-50% of the heavy mineral fraction (Fig. 6). Cr-Spinel (~24%), clinopyroxene (~12%) and Fe-Mg amphibole (~13%) and minor concentrations of rutile (~3%) and apatite (1%) (Fig. 6) form the remainder of the heavy mineral suite. The presence of Cr-spinel suggests that these samples were sourced from a mafic-ultramafic provenance.

Type 2

Type 2 samples are medium- to coarse-grained sandstones that, similar to Type 1 sediments, display varying amounts of diagenetic alteration. Type 2 conglomerate clasts vary from chert- and gabbro-dominated examples to those including a greater proportion and variety of metasedimentary clasts including low-grade phyllite, quartzite and a significant amount of vein quartz. Lithic fragments in the Type 2 sandstones consist of chert, mafic volcanic rocks (primarily basaltic andesite lithics; Fig. 4E), gabbro, and low-

grade metamorphic (phyllite and quartzite; Fig. 4F) rock fragments (Fig. 7). Similar to Type 1, the Type 2 sediments also contain monocrystalline plagioclase (Fig. 4E), clinopyroxene (Fig. 4G), and amphibole. The most distinguishing characteristic of these sediments (compared to Type 1 and 3) is the increased proportion of large monocrystalline and polycrystalline quartz grains (Figs. 4F and H) that vary from relatively undeformed to highly strained.

Modal compositions for 7 samples of Type 2 sediments are characterized by almost equal proportions of lithic fragments and quartz, and relatively minor feldspar (Table 1; Fig. 5). The total quartz composition consists primarily of chert and polycrystalline quartz (Fig. 5). Compared to the Type 1 sediments, feldspar grains in Type 2 sediments are relatively rare, with plagioclase feldspar being the only feldspar present. Lithic fragments consist primarily of volcanic, sedimentary and low-grade metamorphic rocks (Figs. 5). Point-counting results plot solely in the “recycled orogen provenance” field of the QFL of Weltje (2006) and QmFLt plots. The more evolved composition in comparison to the Type 1 sediments is due to the increase in low-grade metamorphic lithic fragments as seen in the LvLILm plot (Fig. 5). Heavy mineral separates from Type 2 sediments sampled from the Kobuk Koyukuk sub-basin indicate a mixed signature of mafic and more intermediate/felsic igneous sources. Dominantly mafic minerals within the Type 2 sediments include clinopyroxene (~37%), Fe-Mg amphibole (~19%), and Cr-Spinel (2%) (Fig. 6). An increased proportion of minerals that are typically hosted in intermediate/felsic igneous rock units characterizes the heavy mineral suite of the Type 2 sediments. This is apparent in the large proportion of

ilmentite (~12%), apatite (~10%), and biotite (~3%) (Fig. 6). The large concentration of sphene is indicative of both sources.

Type 3

Type 3 sediments consist of medium- to coarse-grained sandstones and conglomerates. Type 3 conglomerates are composed of fragments of graphitic schist, quartzite, and quartz-vein material. Lithic fragments within Type 3 sandstones consist primarily of mildly strained schistose (white-mica-rich), polycrystalline quartz + white mica (phengite + paragonite) metamorphic lithics, and minor amounts of chert within a white mica-rich matrix (Figs. 4I - L). Monocrystalline and polycrystalline quartz varies from undeformed to mildly strained (Figs. 4I and L), while albite grains are completely undeformed (fig. 4J).

The modal compositions for 3 samples of Type 3 sediments are composed of almost equal proportions quartz and lithic fragments, with rare occurrences of feldspar (Table 1; Fig. 5). Total quartz compositions consist largely of polycrystalline and monocrystalline quartz with minor amounts of chert (Fig. 5). Feldspar is minor (<10%) and is albitic in composition. Lithic fragments consist primarily of higher-grade metamorphic rock fragments (e.g., schists; Lm) with minor occurrences of low-grade metamorphic lithics (Fig. 5). In contrast to the other two sedimentary types, Type 3 sediments contain no volcanic lithics. In the QFL and QmFLt plots, the Type 3 sediments plot solely within the “recycled orogen” field. In the lithic composition plot, all samples plot close to the higher-grade metamorphic vertices’ with a minor proportion (<25%) of low-grade metamorphic lithics (Fig. 5). Modal abundances of Type 3 heavy

minerals indicate a drastic difference in mineral composition from Type 1 and 2 sediments. Type 3 samples contain a large portion of rutile (30%) and REE-rich accessory minerals including apatite (~10%), monazite (~5%), and xenotime (~1%) (Fig. 6). The appearance of these accessory minerals combined with the presence and abundance of chloritoid (~35%) suggests that these samples were sourced from a medium grade (mid to upper greenschist facies) metamorphic provenance (Fig. 6).

Cr-spinel data

Since the chemical composition of chromium (Cr)-spinel [(Mg,Fe²⁺)(Cr,Al,Fe³⁺)₂O₄] in mafic and ultramafic rocks is influenced by factors such as magma composition, crystallization sequence, oxygen fugacity, and P-T conditions, their composition can be helpful in determining the tectonic setting of their source regions (Dick and Bullen, 1984; Arai, 1992, 1994a,b; Zhou and Robinson, 1997; Barnes and Roeder, 2001; Kamenetsky et al., 2001; Arai et al., 2011). Cr-spinel, due to its refractory nature, is commonly found in sediments deposited proximal to exposures of mafic-ultramafic rocks. During fractional crystallization or partial melting, Cr and Mg are strongly partitioned into the solid, and Al strongly partitioned into the melt (Dick and Bullen, 1984). Thus the geochemistry of detrital Cr-spinel in sedimentary rocks gives important insights into the nature of these source regions. Examining the chemistry of detrital spinel allows constraints to be placed on the overall petrological and geochemical characteristics and variations across source regions.

A ternary plot of the major trivalent cations (Cr³⁺, Al³⁺, and Fe³⁺) is commonly used to distinguish between continental mafic intrusions and other igneous suites (Barnes

and Roeder, 2001). Type 1 and 2 detrital Cr-spinels from the Kobuk Koyukuk sub-basin lie within the overlapping ophiolite and island arc fields (Fig. 7A). In the Cr# $[\text{Cr}/(\text{Cr} + \text{Al})]$ versus Mg# $[\text{Mg}/(\text{Mg} + \text{Fe}^{2+})]$ plot, the majority of both Type 1 and 2 detrital Cr-spinels (>80%) fall within the forearc peridotite field with minor amounts (<10%) that exhibit solely abyssal peridotite chemistries (Fig. 7B). Detrital spinels from both sediment types are characterized by predominantly low concentrations of TiO_2 (Fig. 7C). Greater than 95% of the detrital spinels yield TiO_2 concentrations that are <1.0 wt%. Kamenetsky et al. (2001) demonstrated that increasing Al activity in the melt-spinel system reduces the partitioning of Ti into spinel. It appears that TiO_2 and Al_2O_3 are negatively correlated in Cr-spinels from MORB but that those with arc origins do not show much correlation. According to Kamenetsky et al. (2001), it is possible to discriminate between lower-Ti (boninites and tholeiites) and higher-Ti (calc-alkaline and high-K) island arc series, as reflected by their spinel composition. In the TiO_2 - Al_2O_3 plot, Cr-spinels from the Type 1 and Type 2 sediments fall within the supra-subduction zone (SSZ) peridotite field, with a minor arc tholeiite basalt (island arc basalt, IAB) signature and even less significant ocean island basalt (OIB) and large igneous province (LIP) signature (Fig. 9A). The fields in Figure (7D) are based on the fact that diffusivity of Ti and Cr through olivine is low (Scowen et al., 1991) and that the TiO_2 content in volcanic spinel increases from boninites and IAB through MORB and back-arc basin basalts to intraplate basalts. Based on the overlap of MORB and IAB rock chemistries, Ghosh et al. (2012) generated dominant and overlap fields. Similar to the prior plot, Cr-spinels from both sediment types primarily fall within the MORB-IAB overlap field for the TiO_2 -Cr# plot, with the ~25% falling within the IAB dominant field (Fig. 7D).

527

528 *Detrital Zircon U-Pb geochronology*529 Type 1

530 U-Pb geochronology results for detrital zircons separated from Type 1 sediments
 531 are characterized by two main Mesozoic and Paleozoic zircon age populations: Middle
 532 Triassic to Middle Jurassic (~240-160 Ma) and early Cambrian to latest Mississippian
 533 (~525-325 Ma) (Fig. 8). Individual samples of Type 1 sediments do not contain many
 534 Precambrian detrital zircons, yet the combined data from all samples show Precambrian
 535 population at ~700-550 Ma and ~35% of all zircons are >700 Ma. The four samples that
 536 contain the Middle-Triassic to Middle Jurassic (~240-165 Ma) zircon population yield
 537 maximum peak heights ~200 Ma (Fig. 8). One sample (BRJR13-K8a) contains three
 538 zircons that define a peak at 107 Ma (Fig. 8). All samples are characterized by a mid
 539 Cambrian to latest Mississippian (~525-325 Ma) population, with maximum peak heights
 540 around 375-450 Ma (Fig. 8).

541

542 Type 2

543 Probability distribution plots for U-Pb ages of detrital zircons from Type 2
 544 sediments show three major zircon populations: (1) late Early Cretaceous (~115 Ma); (2)
 545 Late Triassic to Late Jurassic (~220-160 Ma) and (3) mid Cambrian to Late
 546 Pennsylvanian (~525-300 Ma) (Fig. 9). The Late Triassic to Late Jurassic (~220-160
 547 Ma) population is characterized by two distinct peaks at ~165 and 200 Ma (Fig. 9).
 548 Similar to the Type 1 sediments, individual samples contain few Precambrian detrital

zircons. Compilation of all Type 2 samples yields Precambrian populations at ~750-550 Ma, ~1100 Ma, ~1450 Ma and ~1850 Ma (Fig. 9).

Type 3

Unlike the other two sediment types observed within the Kobuk Koyukuk sub-basin, probability distribution plots of Type 3 sediments do not yield any Mesozoic detrital zircons and contain a large (55%) proportion of Precambrian zircons (Fig. 10). Type 3 sediments consist primarily of mid Cambrian to latest Mississippian (~525-325 Ma) zircons with a minor component of Neoproterozoic age (~600-550 and 680 Ma) grains (Fig. 10). A broad spectrum of Precambrian age zircons spans from ~2200-950 Ma with peaks at 1070, 1340, 1520, 1630 and 2640 Ma (Fig. 10).

U-Pb geochronology of conglomerate clasts of the Kobuk Koyukuk sub-basin and magmatic zircons from the Ruby Batholith

Gabbro clasts of Kobuk Koyukuk sub-basin conglomerates

The $^{206}\text{Pb}/^{238}\text{U}$ ages of zircons analyzed from one gabbro clast collected from the Type 1 sediments have a weighted mean age of 194 ± 3 Ma (BRJR13-K8B_1) (Fig. 11A). Zircons dated from two gabbro clasts from conglomerate interbedded with Type 2 sediments yield weighted mean ages of 181 ± 3 Ma (BRNF15-58B_1) and 198 ± 3 Ma (BRNF15-58B_2) (Fig. 11B).

Granitic plutons of the Ruby terrane

Samples were collected from three exposures of two separate plutons of the northern Ruby Batholith (Fig. 3). $^{206}\text{Pb}/^{238}\text{U}$ ages of zircons analyzed from one sample of the Jim River Pluton (BRHR14-2) yield a weighted mean age of 109 ± 2 Ma (Fig. 11C). Samples collected from two exposures of the Bonanza Pluton yield weighted mean ages (BRHR14-7 = 112 ± 3 Ma; BRHR14-8 = 110 ± 2 Ma) that overlap within error (Figs. 11D and E). The U-Pb age of the Jim River Pluton is similar within error to the 112 ± 4 whole-rock Rb-Sr isochron age obtained by Blum et al. (1987).

Hf isotopes

Figure 12A shows all the ϵHf_t values for zircons from all three sediment types analyzed from the Yukon Koyukuk province. The late Early Cretaceous zircons within the Type 2 sediments yield ϵHf_t values from -4 to +4, overlapping the Chondritic Uniform Reservoir (CHUR) line (Fig. 12A). Values for the Middle Triassic to Late Jurassic (~240-160 Ma) detrital zircons observed within both Type 1 and Type 2 sediments yield highly juvenile ϵHf_t values between +12 and +16 (Fig. 12A). Lastly, all three sedimentary rock types contain Early Cambrian to latest Mississippian zircons between 525-325 Ma. Epsilon Hf values for this age group produce a wide array of values between -18 and +13 (Fig. 12A). Zircons from 470-390 yield a linear array from the depleted mantle (DM) line at +13 (~470 Ma) to +6 (~390 Ma). Two distinct groups are observed in zircons between ~350-360 Ma (Fig. 12D), a more radiogenic group with ϵHf_t values from +4 to +9 and a less radiogenic group with ϵHf_t values between -22 and -7.

Epsilon Hf values for zircons from Type 1 and 2 conglomerate clasts of gabbro yield juvenile isotopic signatures (+14.3 to +15.1) and fall on the depleted mantle evolution line (Fig. 12B). These ϵHf_t values are consistent with the Middle Triassic to Late Jurassic detrital zircons suggesting a similar source for the conglomerate clasts and the detrital zircon in the sandstones for these two sedimentary groups (Fig. 12B). Analyses of zircons from granitoid samples from the Ruby Batholith yield ϵHf_t values that are less radiogenic than the conglomerate clasts of the Type 1 and Type 2 sediments, ranging from -0.1 to +0.9 (Fig. 12C).

Discussion

Integration of sedimentary composition and heavy mineral data with isotopic analyses of detrital zircons provides insight into the provenance of sandstones and conglomerate units deposited in the Yukon Koyukuk Basin. The wide variety of clast types in the conglomerate and their age and isotopic data, combined with studies of detrital chromium spinel (table 3), suggest various mixed three distinct source areas for the deposits.

Oceanic island arc provenance

The commonly cited model that led to early HP/LT metamorphism in the Brooks Range and Ruby terrane is the accretion and obduction of an oceanic island arc onto the continental margin of the Arctic Alaska microplate during Late Jurassic to Early Cretaceous time (Moore et al., 1994, 2015; Roeske et al., 1995). This led to the thrust emplacement of oceanic- and possible arc-affinity thrust sheets that make up the highest

structural allochthons of the Brookian orogen. However, due to erosion and/or superimposed extension (e.g., Miller and Hudson, 1991), little remains of the collided volcanic arc edifice. Both Type 1 and Type 2 sediments provide the missing record of a now eroded mafic to ultramafic arc-like source, and thus provide critical evidence to our understanding of the tectonic history of the Brooks Range orogen and the disappearance of the now enigmatic terrane that collided to form part of this orogen.

Geochemistry of the majority of detrital Cr-spinels from the Type 1 and 2 sediments exhibit overlapping ophiolite and arc signatures (Fig. 7A) suggesting that they initially crystallized in a forearc setting (Fig. 7B). When plotted on the TiO_2 vs. Al_2O_3 plot, low TiO_2 values suggests a dominantly supra-subduction zone chemistry with a minor arc tholeiitic signature (Fig. 7C). The presence of these spinel compositional signatures (supra-subduction and arc) suggests an immature arc that likely developed on MORB-type crust. Subduction of oceanic crust beneath MORB-type crust causes a release of volatiles that hydrate and lead to partial melting of the overlying mantle wedge. This partial melt is enriched in fluid-mobile trace elements, giving the hybridized mantle source the distinct trace element signature of arc melts (Plank and Langmuir, 1988; Conder et al., 2002). Geochemical trends of the mafic- to ultramafic-rock units of the Misheguk Mountain allochthon of the Angayucham terrane are transitional between MORB- and arc-types (Harris, 1995). These similarities suggest that a primitive arc source region once covered a much greater region than do the current remaining exposures of the Misheguk Mountain allochthon. The proximity of these sediments to the Brooks Range and Ruby terrane, and their geochemical similarities to rocks of the

Misheguk Mountain allochthon, suggests that the source region for Yukon Koyukuk Basin sediments was the arc that collided to form the Brookian orogen.

Detrital zircons ages along with the age of gabbroic clasts from Type 1 and 2 sediments define a distinct age population between 240 and 165 Ma. Presently there are no rocks of this age range recognized anywhere near or surrounding the Yukon Koyukuk province. Within the center of the basin, the Koyukuk terrane is characterized by a thick sequence of Middle Jurassic to Early Cretaceous mafic to intermediate volcanic, volcanoclastic, and minor intrusive rocks (Box and Patton, 1989), which may represent a possible source region for detritus. The discrepancy in age and composition (too felsic) between the rock units of the Koyukuk terrane and the detritus in Type 1 and 2 sediments indicates that the Koyukuk terrane was not a major contributor to Yukon Koyukuk Basin sediments. Cr-spinel geochemistry from the Angayucham terrane yield Cr# similar to those of the Kobuk Koyukuk sub-basin sediments (Harris, 1995). The Cr# values from the Angayucham terrane vary from 0.32 to 0.76, while those of the Kobuk Koyukuk sub-basin sediments range from 0.17 to 0.86, indicating that the Angayucham terrane likely sourced the mafic- to ultramafic-rich sediments of the basin and was once much more broadly represented across this region.

Along the southern margin of the Brooks Range, the rocks of the Angayucham terrane structurally overlie a regionally extensive top-to-the-south (present day coordinates) extensional shear zone (Gottschalk and Oldow, 1988; Christiansen and Snee, 1994; Law et al., 1994; Little et al., 1994). After collision and obduction of the ocean island arc onto the continental margin, subsequent extension displaced and down-dropped the highest allochthons such that they may now make up the basement of the Yukon

Koyukuk province (Miller and Hudson, 1991). Suggesting that the exposed volcanic rocks observed in the center of the Yukon Koyukuk province may represent the uppermost and youngest (?) portion of the colliding arc or record continued post-collision arc volcanism as suggested by Box and Patton (1989).

Hf isotope compositions (ϵHf) for detrital zircons with ages ranging from 240 and 165 Ma from Type 1 and 2 sediments and from zircons in gabbro clasts range from +12 to +16 (Fig 12B). This narrow range of ϵHf lies close to or on the Triassic-Jurassic depleted mantle evolution line suggesting extraction from a mantle source similar to MORB (Vervoort et al. 2017). The juvenile ϵHf values suggest that the magmas experienced little to no contamination from older continental crust, either in the melt source region or via crustal assimilation (Jones et al., 2015). As a first-order observation, the Hf isotopic data are consistent with derivation of the arc magmas from one type of primary magma extracted from a mantle source with little influence from subducted sediment flux and/or oceanic crust. The lack of evidence for assimilation or contamination of the magmas with continental crust strongly supports our interpretation that the island arc developed in an oceanic setting. Highly juvenile ϵHf and ϵNd values are observed in active extensional oceanic island arc settings. For example, ϵHf and ϵNd values from the western portion of the Aleutian island arc indicate little measurable effect of crustal or other lithospheric assimilation within the arc magmas (Yogodzinski et al., 2010). Our petrologic and geochemical data support the interpretation that a Middle Triassic to early Late Jurassic oceanic island arc, developed upon oceanic crust, ultimately collided with the Brooks Range and Ruby terrane leading to the Jurassic-Cretaceous Brookian orogeny.

The U-Pb geochronology of gabbro clasts and detrital zircons documented here suggests that the production of mafic arc magmatism spanned the Middle Triassic to early Late Jurassic (240-160 Ma). The youngest Jurassic zircons (~165-160 Ma) likely record the time when this period of mafic magmatism ceased. The age of these youngest zircons are consistent with the timing of contact metamorphism recorded beneath the basal thrust of the Misheguk Mountain (first, highest) allochthon of the Angayucham terrane (165-170 Ma), recording the onset of southward-directed subduction of the Arctic Alaska continental margin (present day coordinates) and closure of the Angayucham oceanic basin and obduction of the arc (Wirth and Bird, 1992).

Unroofing of the Brooks Range and Ruby terrane

Previous geologic mapping in the study area has shown that the lowest exposed units of the Kobuk Koyukuk sub-basin are coarse-grained sandstone and conglomerate and fine-grained turbidites dominated by mafic igneous clasts and lithics (Fig. 3; Patton et al., 2009; Dillon, 1989). Lithologic descriptions of Type 1 sediments described herein are similar to the lowermost mafic- to ultramafic-rich conglomerate and sandstone units in the Kobuk Koyukuk sub-basin described by these previous authors. The Type 1 sediments also contain mafic- to ultramafic-rich detritus observed in thin-section and in heavy mineral suites (Figs. 4 - 6). The correlation of the Type 1 sediments with mafic- to ultramafic-rich units of Patton et al. (2009) suggests that the Type 1 sediments may represent the lowermost sedimentary rock unit in the Kobuk Koyukuk sub-basin. Type 1 sample BRJR13-K8a yields a maximum depositional age of 107 Ma. This maximum depositional age is in agreement with latest Early Cretaceous (Albian) ammonite and

pelecypod fossils documented in the mafic- to ultramafic-rich unit (Patton and Miller, 1973). Thus we interpret this age to approximate the initiation of deposition in this part of the Kobuk Koyukuk sub-basin.

Previous mapping along the intersection of the Brooks Range and Ruby terrane (Fig. 3) indicates that the mafic- to ultramafic-rich sediments are overlain by a sequence of non-marine to marine sediments composed of low-grade metasedimentary rock fragments (i.e. phyllite), gabbro clasts, and lithics, with abundance of granitic clasts increasing along the western flank of the Ruby terrane (middle molasse unit of Dillon, 1989). This unit is not differentiated from lowermost units of Patton et al. (2009). Petrographic observations and compositional data of the Type 2 sediments show a systematic variation from the Type 1 sediments in terms of the increased occurrence of abundant low-grade metamorphic (phyllites and quartzites) and undeformed to deformed polycrystalline quartz fragments (quartz grain detritus; Figs. 4 and 5). Conglomerate and sandstone lithologic descriptions of the Type 2 sediments, which are composed of chert, gabbro, and a variety of low-grade metasedimentary rock types including phyllite, slate, quartzite, and quartz vein fragments are comparable to those described by Dillon (1989). U-Pb of detrital zircons of the Type 2 sediments yield U-Pb zircon ages as young as ~105 Ma (Supplementary Table 4), consistent with Albian ammonites and Albian to Cenomanian flora (Patton and Miller, 1973) observed within correlated Type 2 sediments.

Potential source areas for the Kobuk Koyukuk sub-basin that yield zircons of this age consist of a series of late Early Cretaceous to early Late Cretaceous intermediate to felsic plutons that intrude the Yukon Koyukuk Basin and surrounding highlands (except

the Brooks Range) (Fig. 2; 118-78 Ma, K-Ar and U-Pb ages; e.g. Miller, 1989; Roeske et al., 1995, 1998). Proximal to the study area, an eastern calc-alkalic suite of tonalite, granodiorite and granite plutons yield K-Ar ages of 78-89 Ma (Miller, 1989). Although there are no U-Pb ages from these plutons, the K-Ar ages are minimum ages for the Yukon Koyukuk plutons. Intrusion of this suite into hornblende-bearing volcanic rocks (120 ± 3 Ma, K-Ar) and sediments yielding Aptian (126-113 Ma) dinoflagellates suggest that the plutons are no older than late Early Cretaceous. Another potential source area is a suite of late Early Cretaceous biotite granite and granodiorites that intrude the authothonous and allochthonous units of the Ruby Terrane (Fig. 3). The age of the Ruby batholith is determined by several methods (e.g., U-Pb, Rb-Sr, and K-Ar), with ages that range from about 98-118 Ma (Blum et al., 1987; Patton et al., 1987; Miller, 1989; Roeske et al., 1995).

Both the southern Brooks Range and Ruby terrane are composed of similar allochthonous units consisting of mafic-ultramafic rocks of the Angayucham terrane and low-grade metamorphic rocks. The low-grade metamorphic units of both regions are composed of phyllites, slates, and proto-mylonitic- to mylonitic-quartzites (Dillon, 1989; Dover, 1994; Moore et al., 1994). Population density plots of U-Pb ages of detrital zircons from Type 2 sediments show three major populations: (1) late Early Cretaceous (~115 Ma); (2) Late Triassic to Late Jurassic (~220-160 Ma) and (3) mid Cambrian to Late Pennsylvanian (~525-300 Ma; peak max at 413 Ma) (Fig. 9). A cumulative probability distribution plot of all Type 2 samples display a spread of ages including ranges of ~750-550 Ma, ~2000-900 Ma, and ~2850-2300 Ma (Fig. 14A). To determine the source of zircons for Type 2 sediments, detrital zircon ages from low-grade

metamorphic quartzites of the Brooks Range and Ruby terrane are compared to the Yukon Koyukuk Basin data in figure 13A. Excluding the Mesozoic zircons (<260 Ma), detrital zircons ages for the Type 2 sediments are comparable in their cumulative probability distribution with quartzite samples from the Brooks Range and Ruby terrane (Fig. 13A). Both the Type 2 and Brooks Range and Ruby terrane samples contain a significant proportion ($\geq 50\%$) of Paleozoic zircons. The steady increase between 900 – 2000 Ma observed in the Type 2 cumulative probability distribution likely reflect the mixture of Neoproterozoic and Mesoproterozoic zircons between sedimentary sources from the Brooks Range and Ruby terrane. We therefore suggest that the cumulative probability distribution observed for Paleozoic and older zircons from Type 2 sediments record the erosion of low-grade metamorphic rocks from the southern Brooks Range and Ruby terrane (Fig. 13A).

To further distinguish the source of the 115 Ma zircon age population, samples of the Ruby Batholith were collected for U-Pb and Lu-Hf analyses. Due to their remote nature, no samples were analyzed of the Early to Late Cretaceous plutons of the Koyukuk terrane. However, based on estimated crystallization ages of 90 Ma (Eastern) and 105 Ma (Western) (estimated from published K-Ar ages; Arth et al., 1989a) and exposures of the granites observed intruding the mafic- to ultramafic-rich lithic unit, suggests that emplacement of these plutons occurred subsequent to deposition. Conversely, weighted mean ages for zircons from the three exposures (two separate plutons) of the Ruby Batholith agree with those dated from Type 2 sediments (Figs. 9 and 11C-E). U-Pb ages for exposures of the Ruby Batholith vary from 109 to 111 Ma and have ϵ_{Hf} values that vary from -0.1 to +0.9. U-Pb ages and ϵ_{Hf} values of the late Early Cretaceous detrital

zircons (~115Ma) of the Type 2 sediments of the Kobuk Koyukuk sub-basin correspond with those of the Ruby Batholith (Fig. 12C). The similarity in U-Pb and Hf signatures in addition to the fact that the late Early Cretaceous grains were only observed in the more easterly sampled sediments (Fig. 3) suggests that this population was sourced from the Ruby Batholith.

The geology of the southern Brooks Range and Ruby terrane is similar in terms of their structural stratigraphy. The major difference between the two regions is the presence of late Early Cretaceous (118-109 Ma; Roeske et al., 1995; Roeske et al., 1998; this study) granites and granodiorites that intrude older rocks of the Ruby terrane. The composition of Type 2 sediments combined with their detrital zircon U-Pb ages suggest they were likely derived from both the southern Brooks Range and Ruby terrane. Modal mineral abundance results trend toward a more evolved recycled orogen source (Fig. 5), reflecting the progressive erosion and denudation of these two metamorphic highlands. The similarity in detrital zircons patterns (> 260 Ma and older) of the Type 2 sediments with quartzites of the Brooks Range and Ruby terranes suggests that these rock units may have sourced the Paleozoic to Proterozoic zircons. Lastly, comparison of the late Early Cretaceous zircons with those of the Ruby Batholith indicated that uplift and erosion of Ruby terrane also sourced sediments that were deposited into the Kobuk Koyukuk sub-basin.

Type 3 sediments consist of conglomerates with quartz veins and graphitic schist clasts and medium- to coarse-grained lithic sandstones primarily composed of mildly strained schistose (white mica-rich) lithics, polycrystalline quartz + white mica metamorphic lithics, and minor amounts of chert within a white mica matrix (Figs. 4I -

L). Based upon field/petrographic observations, the Type 3 sediments of this study are similar to lithologic descriptions of the uppermost conglomerate and non-marine sandstone unit of Patton et al. (2009) and Dillon (1989). Fossil flora reported from these types of sediments are Albian to Cenomanian in age (Dillon, 1989, Nilsen, 1989). A K-Ar age 86 Ma (Nilsen, 1989) for an ash-fall tuff and ~90 Ma maximum depositional age (Hoiland et al., 2017) suggest that deposition of the Type 3 sediments was ongoing into the Late Cretaceous.

Metamorphic rocks of the southern Brooks Range and Ruby terrane are composed of upper-greenschist to epidote-amphibolite grade (locally granulite facies in Ruby Terrane) metasedimentary and meta-igneous units (volcanic and plutonic).

Compositional data of the metamorphic lithic-rich Type 3 sediments suggest that the metamorphic rocks of these two regions were source area for these sediments (Fig. 5). The presence of metamorphic accessory minerals (rutile, monazite and xenotime) with abundant metamorphic chloritoid observed within the heavy mineral suites of Type 3 sediments support this interpretation (Fig. 6).

In contrast to the other two sediment types, detrital zircons analyzed from the Type 3 sediments yielded no Mesozoic ages (Fig. 10). These sediments are composed of a large proportion (~30-35%) of mid-Paleozoic (360-490 Ma) zircons. The majority of Precambrian zircons are between 950-1750 Ma with minor amounts around 2000 and 2700 Ma. Comparisons of cumulative distribution plots of Type 3 sediments with published results from higher-grade metamorphic rock of the Brooks Range and Ruby terrane suggest that the sediments could have been sourced from either highland (Figs. 13B-C; Bradley et al., 2007; Hoiland et al., 2017). Recently published zircon Hf isotopic

data from the Schist Belt indicate two major Paleozoic groups: a 480-360 Ma group characterized by juvenile to slightly evolved signature (-7 to +15), and a younger (390-360 Ma) mature population (-18 to -7) (Fig. 12D; Hoiland et al., 2017). Epsilon Hf values for Paleozoic zircons of all three sediment types fall within both of these regions indicating the dominance of zircons derived from the Brooks Range into the sediments of the Kobuk Koyukuk sub-basin (Fig. 12D). Due to the lack of zircon Hf data from the Ruby terrane, it is difficult to confirm that the provenance of the Type 3 samples was not from this region as well. However the lack of zircons from Cretaceous plutons or fragments of higher grade (amphibolite to granulite facies) rocks typical of the Ruby terrane suggests source of Type 3 sediments as the Brooks Range. These results are expected based on the nonmarine nature of the Type 3 sandstones and conglomerates and the physical distance away from the Ruby terrane in comparison to the other two sedimentary rock types.

Based on a comparison of the different types of sediment collected in this study with the lithologic descriptions of the sediments, it is evident that the sediments of the Kobuk Koyukuk sub-basin portion of Yukon Koyukuk province reflect the unroofing of the nearby southern Brooks Range and Ruby terrane metamorphic highlands. This was previously suggested based on the visual identification of lithic fragments and conglomerate clasts by Dillon (1989). The lowest part of the sedimentary succession sampled, represented by Type 1 conglomerate and sandstone, record the erosion of the highest allochthon (Angayucham terrane) of the Brooks Range. This is apparent in the mafic- to ultramafic-rich detritus observed in thin-section, gabbroic conglomerate clasts, and mafic heavy mineral suites. Type 2 sedimentary rocks also contain a significant

amount of volcanic lithics but a greater amount of low-grade metamorphic lithics such as phyllites and strained quartzites. This reflects the subsequent exposure and erosion of the low-grade metamorphic rocks of the allochthons structurally below the Angayucham terrane. Lastly, what we infer to be the stratigraphically youngest part of the succession, represented by Type 3 sandstones and conglomerates, has no volcanic lithics and is composed primarily of higher-grade metamorphic lithics with <25% low-grade metamorphic lithics. The presence of predominantly metamorphic lithics and detrital zircon populations in Type 3 sediments reflect the final denudation and exposure of the metamorphic core of the southern Brooks Range. Compositional plots show the progressive maturation of Kobuk Koyukuk sub-basin sediments with stratigraphic position (Fig. 5). In summary, sedimentary point-counts and heavy mineral analyses accompanied by U-Pb dating and Hf isotopic signatures of detrital zircons of sediments of the Kobuk Koyukuk sub-basin reflect the erosional unroofing history of the adjacent southern Brooks Range and Ruby terrane orogenic highlands.

The deposition of conglomerates and coarse-grained clastic sedimentary units adjacent to the orogen-scale, south dipping normal fault along the southern margin of the Brooks Range reflect the occurrence of syn-faulting sedimentation and not necessarily the arc volcanics within the center of the basin as suggested by Till et al., (1993). Maximum depositional ages obtained by U-Pb geochronology of detrital zircons from the lowermost, Type 1 sediments suggest that basin margin fill in the Kobuk Koyukuk sub-basin occurred no earlier than the latest Early Cretaceous (107 Ma) and continued into Coniacian (89.8 – 86.3 Ma) time. Moore et al., (2015) claim that northward propagation of thin-skin thrusting and foreland basin deposition that led to the formation of the

Brooks Range ended by the earliest Cretaceous. The age of this convergent event is significantly older than the timing of basin formation implied by the detrital zircon geochronology results. Therefore it seems likely that formation of the Kobuk Koyukuk sub-basin and Yukon Koyukuk Basin as a whole developed due to extension, and not due to foreland basin subsidence, in the latest Early Cretaceous.

Triassic – Jurassic Paleogeography

Early Mesozoic paleogeographic reconstructions of the North American Cordillera invoke eastward subduction beneath several offshore island arc terranes (e.g., Colpron et al., 2007; Nelson et al., 2013; Shephard et al., 2013; Fig. 14). The timing of magmatism in these arcs is supported by the recognition of abundant Triassic volcanic ash beds and Late Triassic shifts to juvenile ϵNd recorded in the Sverdrup Basin (Patchett et al., 2004; Midwinter et al., 2016). Our identification of Middle Triassic to early Late Jurassic island arc magmatism developed outboard of the Arctic Alaska plate margin supports the interpretation for a continuation of the offshore Canadian Cordillera arc systems along strike into northern Alaska. Northern Alaska, however, is rifted from its original position along the Canadian Arctic margin (Grantz et al., 1998, 2011; Gottlieb et al., 2014). Our findings indicate that the pre-rotated Arctic Alaska continental margin, which formed a northward continuation of the Canadian margin, was also tectonically active during the Triassic and formed a continuation of the active Canadian Cordillera margin (Fig. 14). The timing and subduction polarity inferred for the offshore arc system in the Canadian Cordillera by Nelson et al. (2013), however, differs from the Late Jurassic oceanward-directed subduction of the Angayucham ocean basin and

subsequently the Arctic Alaska continental margin beneath an offshore arc, creating the Brookian orogen (Fig. 14; Wirth and Bird, 1992; Patton and Box, 1989; Moore et al., 1994, 2015).

During the Triassic to Jurassic, subduction beneath the western flanks of peri-Laurentian offshore terranes led to renewed magmatism in the Triassic to Jurassic Quesnellia and Stikine arcs and rifting/oroclinal bending of the Stikine terrane away from the North American Cordilleran margin (Barker, 1994; Childe, 1997; Miller et al., 2002; Nelson et al., 2013 and references therein). Plate tectonic reconstructions of Pangea in the Triassic suggest that the Arctic was a re-entrant that likely led to the recorded differences between the tectonic history of the Canadian Cordilleran margin and the along strike portion of this margin in the Arctic (Fig. 14; Lawver et al., 2002; Golonka, 2011; Shephard et al., 2013; Hadlari et al., 2017; Miller et al., 2017). Despite discrepancies in the timing of events, the overall similarity in Triassic to Jurassic eastward-directed subduction leading to the closure of Late Devonian to Jurassic back-arc ocean basins supports a continuation of the northern Cordilleran paleo Pacific margin into the Arctic (Fig. 14).

Cretaceous Paleodrainage between flanking Brooks Range basins

Moore et al. (2015) characterized the synorogenic Upper Jurassic to Lower Cretaceous strata of the Brookian sequence in the western Brooks Range and Colville foreland basin. Their work showed that the oldest (structurally highest) deposits of the Okpikruak Formation were derived from a volcanic arc source and are composed chiefly of Late Jurassic zircons (maximum peak height $\approx$ 155 Ma). The Okpikruak Formation

contains a higher proportion of mafic minerals, plagioclase feldspar grains, and volcanic lithic fragments which Moore et al., (2015) interpreted to derive from the Angayucham terrane. Younger synorogenic strata contain decreasing amounts of ophiolite and arc debris and display a broadly distributed late Paleozoic to Triassic (359-200 Ma) zircon population (Fig. 15). Moore et al. (2015) stated that these sediments were sourced from a thick succession of Triassic turbidites in Chukotka and shed detritus laterally into the ancestral foreland basin and Colville Basin. Interestingly, the synorogenic sediments from the western Brooks Range and Colville foreland basin are strikingly different from those discussed in this study. Type 1 and 2 sediments of the Kobuk Koyukuk sub-basin share characteristics with those of the mafic (structurally highest) deposits of the western Brooks Range. Yet, the sediments of the Kobuk Koyukuk sub-basin do not contain a large proportion of Late Jurassic ~160-155 Ma zircons (Fig. 15). Proximally sourced gabbroic cobbles from Misheguk Mountain allochthon of the Angayucham terrane and detrital zircons of the Type 1 and 2 sediments suggest a much older Middle Triassic to early Late Jurassic magmatic history for the Angayucham terrane. Late Jurassic ages from granodiorite cobble clasts and the detrital zircons characteristic of the synorogenic strata of the western Brooks Range described by Moore et al. (2015) suggest instead a source from eastern Chukotka, rather than derivation from the Angayucham terrane of the Brooks Range.

Strata of equivalent age in the Colville Basin (late Early Cretaceous [Albian] Nanushuk Fm.) are characterized by a distinct late Paleozoic to Triassic (359-200 Ma) zircon population (Fig. 15). This characteristic zircon population is not observed in any of the samples analyzed from the Kobuk Koyukuk sub-basin (Fig. 15). Our data,

combined with the results of Moore et al. (2015), suggest that the two major basins that flank the Brooks Range received sediments from two completely different source regions. Detrital zircons ages presented in this study indicate that sediments of the Kobuk Koyukuk sub-basin were sourced proximally from the southern Brooks Range and Ruby terrane metamorphic highlands while Moore et al. (2015) conclude that sediments of the Colville Basin were primarily derived from a western source in Chukotka. Our new provenance results combined with paleocurrent data of Dillon et al., (1981, 1987, 1989; Fig. 3) suggest that the sedimentary rocks of the Kobuk Koyukuk basin were derived from a system of smaller drainages that locally transported sediment from the adjacent southern Brooks Range and Ruby terrane highlands. This interpretation implies that the Brooks Range orogen acted as a drainage divide, diverting sediments eroded from the more southerly Angayucham terrane and metamorphic core of the orogen to the south in the Kobuk Koyukuk sub-basin, while sediments derived from eastern Russia laterally filled the Colville Basin to the north. This is supported by the lack of high-pressure amphiboles (glaucophane and crossite) and garnets found in the heavy mineral separates in the Kobuk Koyukuk sub-basin. High-pressure amphiboles were observed in sandstones of Nanushuk Fm. within the Colville Basin, which was interpreted as being derived from erosion of the Brooks Range (Till, 1992). Detrital zircons from sediments in the Kobuk Koyukuk sub-basin indicate a Brooks Range source region and sediments of the Colville Basin suggesting a western source in Chukotka, it is the our interpretation that the high-pressure and amphiboles observed in the Colville Basin are not derived from the Brooks Range metamorphic highlands but from a western source.

Conclusions

Integration of U-Pb geochronology and Lu-Hf isotopic data with provenance analysis of basin margin sediments of the Kobuk-Koyukuk sub-basin of the Yukon Koyukuk Basin suggest:

- 1) Deposition in the Kobuk-Koyukuk sub-basin initiated or was ongoing in the late Early Cretaceous (Albian, ~107 Ma) based on maximum depositional ages of the lowest coarse-grained sediments.
- 2) Cr-spinel and isotope compositions of detrital zircons and gabbro conglomerate clasts indicate that a Middle Triassic to earliest Late Jurassic (240-160 Ma; peak maximum ~200 Ma) juvenile arc terrane sourced the mafic- to ultramafic-rich sediments of the eastern part of the Yukon Koyukuk province.
- 3) Mafic and ultramafic rocks of the Angayucham terrane of the southern Brooks Range and Ruby terrane are the likely source of the Kobuk Koyukuk sub-basin sediments, and represent what remains of a more extensive Middle Triassic to early Late Jurassic oceanic arc terrane obducted onto the continental margin during formation of the Brooks Range fold and thrust belt
- 4) Arc magmatism of the Angayucham terrane is coeval with mafic arc magmatism in the Canadian Cordillera. This suggests a northward

continuation of this offshore arc system, which resulted from subduction
outboard of the outer Canadian continental margin in a cratonward direction.

- 5) The general stratigraphic evolution of the Kobuk-Koyukuk sub-basin
sediments is the result of tectonic and/or erosional unroofing of the adjacent
southern Brooks Range and Ruby terrane. Mafic- to ultramafic-rich
sediments record the initial erosion of the structurally highest Angayucham
terrane and associated mafic volcanic arc edifice. Continued uplift, exposure,
and denudation of the structurally deeper metamorphic rocks are revealed by
the progressive appearance of low-grade and then eventually higher-grade
metamorphic lithic detritus within the sediments of the basin.
- 6) Differences in detrital zircon signatures between similar age strata in the
slightly older syn-orogenic Okpikruak Formation in the Brooks Range and
coeval sediments of the Colville foreland basin to those of the Kobuk
Koyukuk sub-basin indicate that the sediments that fed the two basins were
derived from two different source regions. The Brooks Range orogen acted as
a drainage divide during mid Cretaceous deposition.

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Figure Captions

Figure 1

Terrane and basin map of central and northern Alaska, modified from Moore and Box (2016). Abbreviations: KKB – Kobuk Koyukuk sub-basin; KT – Koyukuk terrane; LYB – Lower Yukon sub-basin; RT – Ruby terrane orogenic belt; SP – Seward Peninsula. Designation for two sub-basins from Patton (1973).

Figure 2

Generalized map of the Yukon Koyukuk Basin of west central Alaska, showing location of Figure 3 (box). Map (adapted from Patton et al., 2009) displays distribution of lithotectonic terranes, Cretaceous sediments, intrusive rocks, and major structures. Abbreviations: KKB – Kobuk Koyukuk sub-basin; LYB – Lower Yukon sub-basin.

Figure 3

Simplified geologic map of the northeastern Kobuk Koyukuk sub-basin showing sample locations, rivers, roads, and towns (modified from Patton et al., 2009). Symbols indicate localities where samples were collected for U-Pb geochronology, U-Pb detrital zircon results of Hoiland et al. (2017) and paleocurrent data from Dillon et al. (1981, 1987, 1989). Abbreviations: BP – Bonanza Pluton; JRP – Jim River Pluton.

Figure 4

Photomicrographs of three sediment types from the Kobuk Koyukuk sub-basin. (A) Type 1 sediment with characteristic chert lithic and monocrystalline plagioclast (Ca-rich)

1615 grains. (B) Volcanic lithic in Type 1 sandstone unit. (C) Gabbroic lithic in Type 1
 1616 sandstone. (D) Low-grade metamorphic lithic (quartzite) in Type 1 clastic rock. (E)
 1617 Monocrystalline plagioclase and volcanic lithics (basaltic andesite composition) with
 1618 plagioclase laths in plagioclase microlite matrix in Type 2 sandstones. (F) Undeformed
 1619 and deformed polycrystalline quartz aggregates in Type 2 sandstone. (G) Unaltered
 1620 clinopyroxene grain in Type 2 sandstone. (H) Minimally deformed, coarse-grained
 1621 polycrystalline quartz grain in Type 2 sandstone. (I) Metamorphic lithic-rich Type 3
 1622 sediment displaying characteristic high-grade quartz + white mica quartzites and
 1623 deformed polycrystalline quartz grains in white mica matrix. (J) Albite feldspar in Type
 1624 3 sandstone. (K) Schistose metamorphic lithic in Type 3 sandstone. (L) Chert and
 1625 unstrained to strained monocrystalline quartz in Type 3 sandstones. Abbreviations: Ab –
 1626 albite; Cht – chert; Chl – chlorite; Cpx – clinopyroxene; Ep – epidote; Gab – gabbro; Ll –
 1627 low-grade metamorphic lithic; Lm – high-grade metamorphic lithic; Ls – sedimentary
 1628 lithic; Lv – volcanic lithic; Qm – monocrystalline quartz; Qp – polycrystalline quartz.

1629

1630 **Figure 5**

1631 Ternary diagrams showing variation in the modal compositions of late Early to Late
 1632 Cretaceous sedimentary rocks from the Kobuk Koyukuk sub-basin. Note the
 1633 compositional changes from Type 1 to Type 3 clastic rocks, believed to record an age
 1634 progression in the provenance for the sequence (see text). Type 2 and Type 3
 1635 sedimentary rocks show a relative increase in quartz and metamorphic (high- and low-
 1636 grade) lithics compared to Type 1 sedimentary rocks. Provenance fields of Dickinson et
 1637 al. (1983) suggest mixed-arc and recycled orogen sources for Cretaceous sediments of the

1638 Kobuk Koyukuk sub-basin. Up-section changes in composition suggest progressive
 1639 unroofing of the surround southern Brooks Range and Ruby terrane. Abbreviations: Q –
 1640 quartz; F – feldspar; L – lithics; Qm – monocrystalline quartz; Lt – total lithics; Qp –
 1641 polycrystalline quartz; Lv – Volcanic lithics; Ls – sedimentary lithics; Ll – low-grade
 1642 metamorphic lithics; Lm – higher-grade metamorphic lithics.

1643

1644 **Figure 6**

1645 Histograms showing the proportion of the different heavy minerals in the late Early to
 1646 Late Cretaceous sedimentary rocks of the Kobuk Koyukuk sub-basin. Note the change
 1647 up-section in composition of heavy mineral populations from mafic-rich in the Type 1
 1648 sedimentary rocks, to a mixture of mafic and felsic/metamorphic in the Type 2, and
 1649 finally to a metamorphic-rich population in the Type 3 sedimentary units. This trend in
 1650 composition is also observed in the decrease up-section in clinopyroxene and Cr-spinel
 1651 and the increase in rare earth element accessory minerals and metamorphic chloritoid.
 1652 Mineral abbreviations from Whitney and Evans (2010).

1653

1654 **Figure 7**

1655 Compositional discrimination plots for Cr-spinel data from Type 1 and Type 2
 1656 sedimentary rocks of the Kobuk Koyukuk sub-basin. (A) Al-Fe³⁺-Cr triangular diagram
 1657 for Cr-spinels. Selected contour lines of the different tectonic settings are from Barnes
 1658 and Roeder (2001). The light gray dashed line encloses 90% of the data for continental
 1659 mafic intrusions. The dark gray dotted line represents the 90% for the island arc tholeiitic
 1660 setting. The black dashed line represents the 90% of the data for ophiolitic settings

(oceanic crust + upper mantle). (B) Cr# $[\text{Cr}/(\text{Cr} + \text{Al})]$ vs. Mg# $[\text{Mg}/(\text{Mg} + \text{Fe}^{2+})]$ tectonic discrimination plot. Fields are from Barnes and Roeder (2001). (C) TiO_2 versus Al_2O_3 (wt%) diagram for chromium spinels (after Kamenetsky et al. 2001). Arc = ocean island arc; LIP = large igneous province; MORB = mid-ocean ridge basalt; OIB = ocean island basalt. Note that the majority of the data plot in the MORB and Arc peridotite fields; some rare spinels (<5%) plot in the OIB and LIP fields. (D) TiO_2 vs. Cr# of chromium spinels and tectonic setting discrimination plot, after Ghosh et al., (2012).

Figure 8

Age-probability distribution for six samples from the Type 1 sandstones. Sample number and number of zircons analyzed are shown next to each curve. Dashed black line indicates age of gabbro cobble clasts collected from Type 1 conglomerate. Light gray bar = 240 – 160 Ma zircon population; Horizontal line column = 525 – 325 Ma zircon population. Arrow = youngest zircon peak, suggestive of maximum depositional age.

Figure 9

Age-probability distribution for eleven samples from the Type 2 sandstones. Short dashed line indicated weighted mean age (110 ± 1 Ma) of three Ruby batholith samples. Dashed black lines indicate ages of two gabbro cobble clasts collected from Type 2 conglomerate. Dark gray bar = ~115 Ma zircon population; Light gray bar = 240 – 160 Ma zircon population; Horizontal line column = 525 – 325 Ma zircon population.

Figure 10

Age-probability distribution for three samples from the Type 3 sandstones. Horizontal line column = 525 – 325 Ma zircon population.

Figure 11

U-Pb zircon ages for gabbro clasts. (A) Weighted mean age for a clast collected from Type 1 sediments (Kmc of Patton et al., 2009). (B) Weighted mean age for two gabbro clasts in Type 2 conglomerate (Kmc of Patton et al., 2009). (C - E) Weighted mean U-Pb zircon ages for intrusive rocks of the Ruby Batholith. MSWD – mean square of weighted deviates.

Figure 12

Hf isotopic data for Phanerozoic detrital zircons from latest Early Cretaceous – Late Cretaceous sedimentary rock units of the Kobuk Koyukuk sub-basin. (A) Epsilon Hf data for all three sedimentary rock types. (B) Hf isotopic data from gabbro cobbles from Type 1 and Type 2 conglomerate units. (C) Epsilon Hf values of late Early Cretaceous detrital zircons compared to Cretaceous plutons of the Ruby Batholith. Note the similarity in zircon age and ϵHf values for detrital zircons for the Type 2 sedimentary rocks and those of the Ruby Batholith. (D) Comparison of Hf isotopic data for all sedimentary rock Types versus published epsilon Hf values for Paleozoic zircons from the Brooks Range (gray region; Hoiland et al., 2017) The majority of the Type 2 and Type 3 Paleozoic detrital zircons fall within the region of zircons results of the Brooks

1706 Range. Abbreviations: BR – Brooks Range; CHUR – chondritic uniform reservoir; DM
1707 – depleted mantle.

1708

1709 **Figure 13**

1710 Age-cumulative distribution plots (CDP) of detrital zircon results from sedimentary rocks
1711 of the Kobuk Koyukuk sub-basin and metasedimentary units from the surrounding
1712 Brooks Range and Ruby Terrane orogenic belts. (A) CDP for >260 Ma zircons from
1713 Type 1 and Type 2 sediments (all samples combined for each sediment type) compared to
1714 detrital zircon results from low-grade metamorphic units from the surrounding Brooks
1715 Range and Ruby terrane (Bradley et al., 2007; Hoiland et al., 2017). (B) CDP for Type 3
1716 (all samples combined) clastic unit compared to detrital zircons results from higher-grade
1717 metamorphic units from the Brooks Range (Hoiland et al. 2017). The Type 3 detrital
1718 zircon signature likely reflects a mixture of these various samples. (C) CDP for Type 3
1719 (all samples combined) sandstones compared to detrital zircons results from higher-grade
1720 metamorphic units from the Ruby terrane (Bradley et al., 2007).

1721

1722 **Figure 14**

1723 Late Triassic-Early Jurassic paleogeographic reconstruction of northern North American
1724 Cordillera illustrating the continuation of offshore Canadian Cordillera arc systems and
1725 cratonward-directed offshore subduction zone along strike into northern Alaska.
1726 Basemap is from C. Scotese's paleomap project (Scotese, 2003). Timing relations and
1727 illustration modified from Miller et al. (2010). Abbreviations: AA – Arctic Alaska.

1728

1729 **Figure 15**

1730 Age-probability distributions for all three sedimentary ‘Types’ observed in the KKB
1731 compared to the Early Cretaceous Okpikruak and late Early Cretaceous (Albian)
1732 Nanushuk formations of the western Brooks Range and Colville Basin (Moore et al.,
1733 2015). Note the lack of Carboniferous – Early Triassic (359 – 250 Ma Ma) and latest
1734 Jurassic – Early Cretaceous (150 – 120 Ma) zircon populations in the KKB sandstones
1735 and the lack of a 200 Ma and 113 Ma peaks in the Okpikruak and Nanushuk formations.