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Key Points:

- The Alaska Range suture zone (ARSZ) represents part of a 2000-km-long crustal boundary that records the tectonic growth of North America
- Detrital zircon U-Pb ages and Hf isotope compositions from the ARSZ record magmatic events associated with global and regional tectonics
- Integration of multiple data sets from detrital zircons provides new insights into sediment provenance in collisional zones

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2

Correspondence to:

M. C. Romero,
mariahc.romero@gmail.com

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Geology, U-Pb Geochronology, and Hf Isotope Geochemistry Across the Mesozoic Alaska Range Suture Zone (South-Central Alaska): Implications for Cordilleran Collisional Processes and Tectonic Growth of North America

Mariah C. Romero^{1,2} , Kenneth D. Ridgway¹, and George E. Gehrels³

¹Department of Earth, Atmospheric and Planetary Sciences, Purdue University, West Lafayette, IN, USA, ²Now at Department of Earth Sciences, Montana State University, Bozeman, MT, USA, ³Department of Geosciences, University of Arizona, Tucson, AZ, USA

Abstract The Mesozoic Alaska Range suture zone is defined by a transition from oceanic to continental terranes and is part of a 2000-km-long tectonic boundary throughout the northern Cordillera. Surface geologic mapping of the rock types across this suture zone provides critical information about the upper crustal configuration but provides little insight into the sedimentary, igneous, and metamorphic processes that occurred in deeper levels of the collisional zone. To better constrain the timing and mantle-crust sources of collision-related magmatism, we combine U-Pb ages and Hf isotope compositions of detrital zircons from the three main components of the suture zone. U-Pb/Hf data sets from inboard, continental margin samples have Precambrian-Paleozoic ages with epsilon Hf(t) values ranging between +10 and −20. U-Pb/Hf data sets from the outboard, oceanic terrane samples have Pennsylvanian-Permian detrital zircon ages with epsilon Hf(t) values between +16 and +10. The U-Pb/Hf data set of detrital zircons from Mesozoic strata that represent intervening sedimentary basin(s) that formed between the continental margin and oceanic terranes record Precambrian-Mesozoic detrital zircon ages with epsilon Hf(t) values between +14 and −20. Results of the study document four Archean and Proterozoic global crustal magmatic events that are correlated to the tectonic growth of Laurentia. Also, three Phanerozoic magmatic events have been identified that represent more regional tectonic events. This study demonstrates that the combination of U-Pb geochronology and Hf isotope geochemistry applied to detrital zircons is a powerful tool to define sediment provenance in collisional zones and delineate episodes of global and regional magmatism along convergent plate boundaries.

1. Introduction

The western margin of North America is the product of oceanic plateaus, island arcs, and previously rifted parts of continental margins that have collided along the convergent margin of Laurentia since late Paleozoic time (Figure 1) (Coney et al., 1980; Colpron & Nelson, 2009; Jones et al., 1982; Monger & Nokleberg, 1996). In the geologic record, suture zones are the end product of these collisional processes. Suture zones are characterized as distinct areas of deformation, magmatism, metamorphism, and sedimentary basin development marking areas where oceanic crust and other outboard crustal fragments have been welded to the former continental margin (e.g., Dewey, 1977; Dewey & Bird, 1970). During this welding process, zircons that are eroded from both continental and oceanic terranes are subsequently deposited in the intervening syn-collisional and post-collisional basins. These detrital zircons contain the genetic signature of crustal evolution of different elements of the collisional zone and the record of related magmatic, metamorphic, and sedimentary processes. Detrital zircons, therefore, can be used as proxies along collisional margins for delineating both the upper crustal response (sediment provenance, deposition, and basin development) and the deeper crustal response (recycling of deeper parts of the crust via igneous and metamorphic processes).

A relatively new approach to studying collisional margins has been the coupling of both detrital zircon geochronology and detrital zircon Hf isotope geochemistry to determine genetic linkages between juxtaposed

Figure 1. Simplified terrane map of the North American Cordillera. Upper Jurassic-Cretaceous sedimentary strata are exposed between the Intermontane Belt and the Wrangellia composite terrane, respectively (see text). MS = Mesozoic sedimentary strata of the Kahiltina assemblage, Nutzotin Mountains sequence, Dezadeash formation, and Gravina belt. (A-H) The comparison of normalized detrital zircon age distribution diagrams from Jurassic-Cretaceous basal assemblages in the North American Cordillera in Figure 12. CSZ = Coast shear zone. Modified from Nelson et al. (2013).

terrane (e.g., Beranek et al., 2013; Gehrels & Pecha, 2014; Malone et al., 2014; Pecha et al., 2016; White et al., 2016). Our study utilizes 3,206 U-Pb ages and 406 Hf isotope compositions from detrital zircons from the three distinct components within the Alaska Range suture zone. These include the metamorphic rocks of the Ancestral North American Mesozoic continental margin, the Paleozoic-Mesozoic igneous and sedimentary rocks of the oceanic Wrangellia terrane, and the intervening sedimentary strata of the

Figure 2. Generalized geology and magnetic domains in south-central Alaska. (A) Simplified geologic map. (B) Regional magnetic potential map of the Alaska Range suture zone in south-central Alaska. Both maps are at the same scale and show a receiver function transect (line A-A') shown in Figure 3. Major faults are outlined by bold black lines in Figure 2A and bold white lines in Figure 2B. Modified from Brennan et al. (2011).

Jurassic-Cretaceous Kahiltina assemblage. The Mesozoic accretion of the Wrangellia composite terrane to the western North American continental margin is recognized as one of the largest known additions of juvenile oceanic crust along this convergent margin (Figure 2) (Csejter et al., 1982; Jones et al., 1977; Nokleberg et al., 1985). This collisional event is interpreted to have occurred sometime between the Early Jurassic to Late Cretaceous time (Manuszak et al., 2007; McClelland et al., 1992; Pavlis, 1982; Trop et al., 2005). The combination of the Lu-Hf isotope system along with independent U-Pb geochronologic information from the Alaska Range suture zone allows us to interpret four Archean and Proterozoic, and three Phanerozoic episodes of crustal growth by magmatic thickening events. We demonstrate that the Archean and Proterozoic magmatic thickening events can be correlated to stages of global crustal growth when juvenile magmas are interpreted to have assimilated crust of multiple ages and different compositions such as during the formation of the supercontinents. The identified Phanerozoic stages of crustal growth appear to be specific to the northwestern Cordilleran margin and may represent periods of magmatic thickening related to the following: (1) processes and cyclicity in Cordilleran arc systems (e.g., DeCelles et al., 2009; Ducea et al., 2015); (2) juvenile magmas assimilating oceanic crust, continental

Figure 3. Common conversion point (CCP) stacked receiver function transect and lithospheric cross section. (A) CCP stacked receiver function transect along cross section A-A'. Location of transect A-A' is shown in Figure 2. Solid black lines represent stacked receiver functions for each column of CCP bins. X-offset shows the distance along the transect A-A', beginning from the northern endpoint. (B) Simplified geologic interpretation of a lithospheric cross section from the CCP stacked receiver function for transect A-A'. Faults: DF = Denali fault, HCF = Hines Creek fault, TF = Talkeetna fault. Lithologic units: CAR = Granitic intrusion (Upper Cretaceous-Eocene); Dy = Devonian Yanert Fork sequence; Kcs = lower Cantwell formation (Cretaceous); KJk = Kahiltina assemblage (Upper Jurassic-Lower Cretaceous); Kms = Melange (Cretaceous); MGMB = Maclaren Glacier metamorphic belt; NG = Nenana Gravels; PzpCp = quartz-sericite schist (Precambrian-Paleozoic); Tcv = Upper Cantwell volcanic rocks (Paleocene-Eocene); Trcs = Calcareous sedimentary strata and undifferentiated rocks (Triassic); UG = Usibelli Group; VCSZ = Valdez Creek Shear Zone. Lower and middle crustal features: AKR = lower and middle crust of the Alaska Range; MOHO = lower crust, upper mantle transition; NAb = lower and middle crust of the Ancestral North American margin; WCT = lower and middle crust of the Wrangellia composite terrane. Strike-slip fault: crossed circle away from reader, dotted circle toward the reader. See Brennan et al. (2011) for more information on receiver function analysis of the transect A-A', and Brennan (2012) for more information on the lithospheric cross section for the Alaska Range suture zone. Modified from Brennan (2012).

crust, and sedimentary strata that have been tectonically juxtaposed in the deeper levels of collisional zones (e.g., Bouilhol et al., 2013; van Hunen & Miller, 2015); and/or (3) other regional magma/crust interactions within an evolving accretionary convergent margin (e.g., Cecil et al., 2011).

We also integrate our new results from the Alaska Range suture zone with previously published studies from along-strike sedimentary basins of the North American Cordillera to show differences in provenance and timing of deposition along this crustal boundary. Our U-Pb/Hf data sets from this study are also one of the first steps in the establishment of a regional Hf database for the Alaska Range and provide a Hf transect across a suture zone. Results from this study show that the integration of U-Pb/Hf data sets is advantageous for constraining the provenance of sedimentary detritus within a suture zone and its connection to collisional processes and continental growth.

2. Geophysical and Geologic Configuration of the Alaska Range Suture Zone

In south-central Alaska, the modern configuration of the Alaska Range suture zone is well defined by surface geology (Figure 2A) (Csejczy et al., 1992; Jones et al., 1977; Ridgway et al., 2002; Trop et al., 2019),

magnetic potential field surveys (Figure 2B) (Saltus et al., 1997), and geophysical receiver function cross sections (Figure 3) (Brennan et al., 2011). The surface geology of the suture zone is characterized by a transition from mainly Paleozoic and Mesozoic metamorphic, felsic-rich rocks of the Ancestral North American margin to Jurassic-Cretaceous sedimentary strata of the Kahiltna assemblage, to Paleozoic-Mesozoic mafic igneous and sedimentary rocks of the Wrangellia composite terrane (Figure 2A). This change in rock types across the suture zone is also well defined in the aeromagnetic and gravity surveys of south-central Alaska (Figure 2B) (Brunstein, 2002; Glen et al., 2007; Saltus et al., 1997, 1999, 2007). The southern Alaska magnetic high in Figure 2B represents a regional high in both gravity and magnetic potential that correlates to the thick, dense mafic rocks of the Wrangellia composite terrane (Glen et al., 2007; Saltus et al., 2007). The southern Alaska magnetic trough labeled in Figure 2B is defined by a low magnetic and gravity signature and generally coincides with the sedimentary strata of the Kahiltna assemblage. We refer to this area as the Kahiltna assemblage in the text because this magnetic domain coincides with the surface distribution of these sedimentary strata. The increased magnetic potential north of the southern Alaska magnetic trough closely follows the surface exposures of the felsic igneous and metamorphic rocks of the Yukon composite terrane (Figure 2). Throughout this paper, we refer to this area as the Ancestral North American margin.

Geophysical cross sections based on stacked receiver function transects coupled with surface geologic cross sections across the Alaska Range suture zone provide a perspective of the lithospheric scale and subsurface configuration of the suture zone. For a detailed discussion of the data processing, construction, and interpretation for the geophysical cross section shown in Figure 3A see Brennan et al. (2011) and Brennan (2012). Linking observations of crustal thickness, intracrustal discontinuities, and V_p/V_s values, Brennan et al. (2011) delineate three major components of the Alaska Range suture zone based on the receiver function cross sections (Figure 3) that are consistent with surface geologic data (Figure 2A) and potential field data (Figure 2B). The Ancestral North American margin (i.e., Yukon composite terrane) along the northern section of the cross section consists of the thinnest crust along the transect (~27-km average thickness), and its low V_p/V_s values are consistent with an abundance of felsic-rich metamorphic rocks in this terrane (e.g., Brennan et al., 2011; Dusel-Bacon, 1994; Foster et al., 1994). The transition from the northern to the central section is marked by a discrete step across the Moho (Figure 3) that has been interpreted to reflect tectonic underthrusting (Brennan et al., 2011). The central section includes the thickest crust along the transect (~37-km average crustal thickness) and has intermediate V_p/V_s values (Brennan et al., 2011). This section corresponds to the surface distribution of the Kahiltna assemblage (Figure 2A) and the southern Alaska magnetic trough geophysical domain (Figure 2B). Brennan et al. (2011) interpret the central section to have an overall intermediate composition. This zone is interpreted to have undergone significant internal deformation as a result of crustal shortening and thickening (Brennan et al., 2011; Ridgway et al., 2002; Trop et al., 2019). Locally along strike, for example, strata of the Kahiltna assemblage have been metamorphosed at depths of ~25 km and rapidly exhumed to the surface in the Valdez Creek shear zone (location shown in Figure 3B—Clearwater Mountains area) (Davidson et al., 1992; Link, 2017; Ridgway et al., 2002). The transition from the central section to the southern section occurs across another significant step in the Moho (Figure 3). The southern section of the Alaska Range suture zone has an average crustal thickness of ~30 km, the highest V_p/V_s values observed along the transect, and is interpreted to represent the mafic rocks of the Wrangellia composite terrane (Brennan et al., 2011).

It is important to note that the Alaska Range suture zone includes several major faults. From north to south, these faults include the Hines Creek fault, the Denali fault, and the Talkeetna fault (Figures 2–4) (Csejtey et al., 1992; Sherwood, 1979; Wahrhaftig et al., 1975). It remains unclear whether these faults formed coevally with Mesozoic collision of the Wrangellia composite terrane to the Ancestral North American margin, or are younger, Cenozoic features exploiting zones of weakness within the Mesozoic suture zone, or perhaps some combination of the two.

2.1. Rock Types and Geologic Development of the Alaska Range Suture Zone

This study focuses on the three first-order geologic components of the Alaska Range suture zone described in the previous section based on published geophysical and geological studies. In this section, we present a brief overview of rock types to provide geologic and stratigraphic context for our sample locations (Figures 4 and 5). For a more detailed geologic explanation of the rocks in the study area, see Text S1 in the supporting information.

Figure 4. Geologic map of south-central Alaska showing Mesozoic-Cenozoic sedimentary basins, Paleozoic-Mesozoic accreted terranes, continental margin assemblages, Mesozoic-Cenozoic accretionary prism, Paleozoic-Mesozoic mélanges, Devonian-Quaternary igneous rocks, and faults. Numbered boxes represent sample locations. The location of a CCP stacked receiver function transect along A-A' is shown. ARSZ = Alaska Range suture zone, BRF = Border Ranges fault, CMF = Castle Mountain fault, DF = Denali fault, DF(E) = Denali fault Eastern, DF(M) = Denali fault (McKinley strand), HCF = Hines Creek fault, NAB = Ancestral North American margin, TF = Talkeetna fault, VCSZ = Valdez Creek Shear Zone, WCT = Wrangellia composite terrane. Gray lines outline 1:250,000 quadrangles. Modified from Wilson et al. (2015).

Rock types of the Ancestral North American margin include Paleoproterozoic cratonic basement, Paleoproterozoic-Triassic strata, and younger cover successions that were deposited along the margin of northwestern Laurentia (e.g., Nelson et al., 2013). Regional metamorphosed pericratonic strata and Devonian-Mississippian plutons in central and eastern Alaska (Figures 1 and 4) are categorized as part of the North American continent margin and the Yukon-Tanana terrane (Dusel-Bacon et al., 2006; Hansen & Dusel-Bacon, 1998, and references therein; Nelson et al., 2006). In the Alaskan and Canadian Cordillera, multiple rock assemblages are identified as part of the Ancestral North American margin (NAB in Figure 1). In south-central Alaska, we focus on the Proterozoic-early Paleozoic Healy schist and the Paleozoic-Mesozoic Wood River assemblage. The Healy schist is exposed in the central Alaska Range and consists of low-grade metamorphic rocks that include quartz-sericite schist, quartzite, and sericite schist (Figure 6A), with minor components of marble and carbonaceous schist (Dusel-Bacon et al., 2004, 2006; Nokleberg et al., 1992; Wahrhaftig, 1968). The Wood River assemblage, exposed in the study area, consists of Paleozoic to Mesozoic metamorphosed lithic sandstone, calcarenite, calcareous slate, quartzite (Figure 6B), chert-pebble conglomerate, argillite, and volcanoclastic rocks (Dusel-Bacon et al., 2004, 2006; Newberry et al., 1997; Umhoefer, 1984). Overall, these Paleozoic and Mesozoic metasedimentary and meta-volcanic rocks have been described as part of a long-lived continental margin with proximity to northwestern Laurentia.

The southern component of the Alaska Range suture zone, as defined by the previously discussed geologic and geophysical data sets, is the allochthonous Wrangellia composite terrane (Figures 1–4). This composite terrane consists of marine sedimentary, volcanic, and metasedimentary strata of the Peninsular, Wrangellia, and Alexander terranes. These rocks are exposed from western Alaska to southern British Columbia and may continue southward to the state of Washington (Gehrels & Saleeby, 1987; Jones et al., 1977; Plafker

Figure 5. Generalized columns that summarize the tectonostratigraphy of the Ancestral North American margin, Kahiltina assemblage, and Wrangellia terrane in south-central Alaska. Red dots represent the tectonostratigraphic location of samples analyzed for this study. Thickness of strata and formations are not to scale. HCF = Hines Creek fault, TF = Talkeetna fault.

& Berg, 1994). In the Canadian Cordillera, the combined Wrangellia and Alexander terranes are referred to as the Insular terrane (Monger et al., 1982). The Wrangellia terrane is interpreted as an accreted oceanic plateau, representing the product of an oceanic flood basalt event that was constructed on a Paleozoic arc (Greene et al., 2008; Israel et al., 2014; Richards et al., 1991). Figure 5 outlines the stratigraphy of the Wrangellia terrane in southern Alaska. Note that andesites, basaltic lava flows, and pyroclastic rocks of the Pennsylvanian Station Creek formation constitute the lower part of the Wrangellia terrane (Gardner et al., 1988). Stratigraphically above the Station Creek formation are thick sections of Permian through Triassic basalt and marine sedimentary strata (Figure 5) (Trop et al., 2002; also see Text S1). This study primarily focuses on detrital zircon samples from the Pennsylvanian-Permian Slana Spur formation that are well exposed in the study area (Figures 6C and 6D); Triassic-Cretaceous strata from the younger part of the Wrangellia terrane are not as well exposed and were not analyzed for this study.

The central section of the Alaska Range suture zone is defined by exposures of the sedimentary strata of the Jurassic-Cretaceous Kahiltina assemblage (Figures 4 and 5). This 3–5-km-thick sequence of submarine fan strata are exposed in both the Alaska Range (Figure 6E) and the northwestern Talkeetna Mountains (Figure 6F) (Hampton et al., 2007, 2010; Ridgway et al., 2002). A Late Jurassic to Cretaceous (Kimmeridgian to Cenomanian) age for the Kahiltina assemblage is based on marine fossils (Bundtzen et al., 1997; Jones et al., 1980, 1982; Reed & Nelson, 1980; Silberling, Richter, & Jones 1981; Silberling, Richter, Jones, & Coney, 1981). More recent studies using maximum depositional ages from detrital zircons are in general agreement with the biostratigraphic ages (Hampton et al., 2007, 2010; Hults et al., 2013; Kalbas et al., 2007).

A key structural element of southern Alaska and western Canada is the Denali fault system (Eisbacher, 1976; Nokleberg et al., 1985; Plafker & Berg, 1994). Geological studies suggest that the Denali fault has undergone ~400–450 km of dextral displacement since the Late Cretaceous (Eisbacher, 1976; Lowey, 1998; Nokleberg et al., 1985; Plafker & Berg, 1994). Paleomagnetic studies suggest approximately $1,650 \pm 890$ km of displacement for the Denali fault (or other interior faults) relative to the stable North America craton during the Late Cretaceous-Early Eocene (80–55 Ma; Stamatakis et al., 2001). Additionally, it is important to note that the northern boundary of the Ancestral North American margin in Alaska (NAb in Figure 1) is the 2000-km-

Figure 6. Photographs of analyzed samples from the Ancestral North American margin, Wrangellia terrane, and Kahiltna assemblage. (A) Isoclinally folded quartz-sericite schist from the Healy schist (sample 073115KR-01). Pink pen for scale. Dashed black lines outline isoclinal folds. (B) Quartzite from the Wood River assemblage (sample GC-052805-01). Hammer for scale. (C) Field view of the Pennsylvanian-Permian Slana Spur formation (samples 081315KR-02 and 072709KR-02). Bedding is steeply to vertically dipping. Person for scale in bottom right. (D) Sandstone bed of Pennsylvanian-Permian Slana Spur formation (samples 081315KR-02 and 072709KR-02) that is exposed along Station Creek. Person for scale. (E) Alternating thick sandstone and mudstone beds of the Kahiltna assemblage in the central Alaska Range. Person for scale. (F) Alternating beds of sandstone (ss) and mudstone (ms) of the Kahiltna assemblage in the northwestern Talkeetna Mountains. Hammer for scale.

long Tintina fault system (Till et al., 2007). Dextral displacement of ~450 km since the Late Cretaceous/early Cenozoic, and 900 km since the Devonian, have been interpreted for this fault system (Gabrielse, 1985; Gabrielse et al., 2006; Plafker & Berg, 1994; Price & Carmichael, 1986). When this displacement is restored, our samples would have been located farther to the southeast relative to the North American craton. Strike-slip displacement along the Tintina and Denali fault systems warrants us to consider potential sources of sediment for our provenance interpretations that are found throughout the North American Cordillera, such as terranes and assemblages in eastern Alaska, Yukon, and British Columbia.

Figure 7. Histogram plots of detrital zircon ages from Proterozoic-Triassic strata of the Ancestral North American margin. The distribution of detrital zircon ages ($n = 1,139$) range between Precambrian-Mesozoic ($pC = 71\%$, $Pz = 29\%$, $Mz = <1\%$), with Precambrian ages as the most abundant. The area under the orange curve represents the relative probability functions of detrital zircon ages.

3. Analytical Methods and Terminology

3.1. U-Pb Geochronologic Analysis

Sample preparation and zircon separation were completed at the Arizona LaserChron Center using standard methods outlined by Gehrels et al. (2008), Gehrels (2012, 2014), and Gehrels and Pecha (2014). Individual zircon grains were randomly selected and analyzed by laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (www.laserchron.org) using a Thermo Element2 single-collector inductively coupled plasma (ICP) mass spectrometer. U-Pb analyses were conducted with a 20- μm spot diameter, resulting in a 12- μm pit depth on each evaluated grain. Zircon grains showing cracks and/or inclusions or that were too small were avoided for U-Pb analyses; BSE images for each detrital sample aided with grain selection. “Agecalc,” the standard reduction protocol used by the Arizona LaserChron Center, allowed for the completion of data reduction for each detrital zircon sample (Gehrels et al., 2008; Gehrels & Pecha, 2014). During the data reduction process, U-Pb data were filtered to exclude ages with high common Pb, >5% reverse discordance, >10% uncertainty, or >20% discordance. The reported ages are based on the $^{206}\text{Pb}/^{238}\text{U}$ ages for grains $< \sim 1.0$ Ga and on the $^{206}\text{Pb}/^{207}\text{Pb}$ ages for grains $> \sim 1.0$ Ga (Gehrels, 2000; Gehrels et al., 2008). Peak ages for each analyzed sample were generated from the “Age Pick” program (Gehrels, 2012). Figures 7–9 show the collective results of the U-Pb detrital zircon analysis for the Ancestral North American margin, the Wrangellia terrane, and the Kahiltna assemblage, respectively. Raw data for U-Pb analysis for each detrital zircon sample are available in Table S1 in the supporting information.

3.2. Hf Isotopic Analysis

Hf isotope analyses of zircon grains were conducted following the analytical procedures outlined by Gehrels and Pecha (2014). Hf isotope analyses were acquired by laser ablation-inductively coupled plasma mass

Figure 8. Histogram plots of detrital zircon ages from Pennsylvanian-Permian strata of the Slana Spur formation of the Wrangellia terrane. The distribution of detrital zircon ages ($n = 741$) are between Precambrian-Cenozoic ages, with Paleozoic ages as the most abundant (pC = 1%, Pz = 98%, Mz = 1%, Cz = <1%). The area under the blue curve represents the relative probability functions of detrital zircon ages.

spectrometry (LA-ICPMS) using a Nu multi-collector inductively coupled plasma (ICP) mass spectrometer. Hf analyses were conducted by placing a 40- μm spot diameter over the preexisting 20- μm pit from the previous U-Pb analysis. Hf laser pits centered on top of the preexisting U-Pb pit allows for the linkage between the zircon crystallization age and the Hf isotope ratio. Between 14 and 55 Hf isotope analyses were conducted for each analyzed sample, to evaluate major detrital zircon age populations. All raw Hf isotope data are available in Table S2. The average uncertainty of each analysis is 2.4 epsilon units, at 2 sigma. Hf isotope compositions for the analyzed samples are shown in Figure 10 using a Hf evolution diagram with epsilon $\text{Hf}_{(t)}$ values representing $^{176}\text{Hf}/^{177}\text{Hf}$ ratios at the time of zircon crystallization relative to the chondritic uniform reservoir (Bouvier et al., 2008).

3.3. Terminology

Our use of the term “reworked” in the text refers to sediment that was physically derived (i.e., eroded) from a sedimentary source and then transported to a new sedimentary basin system; this process may occur multiple times depending on exhumation, unroofing processes, and paleodrainage systems. In contrast, “recycled” is used throughout this paper to refer to successive melting/metamorphic events of older continental crust that may have been originally extracted from the mantle at the time of intersection with the depleted mantle trend line as shown in Figure 10 (e.g., Bahlburg et al., 2009, 2011; Gehrels & Pecha, 2014). Plotted analyses that can be projected along a Hf-evolution trajectory (black arrow in Figure 10) to the depleted mantle trend line or to a separate-age cluster of analyses are interpreted to indicate earlier melting/metamorphic events. Utilizing this terminology of reworked and recycled, we distinguish between interpretations regarding sedimentary processes and melting events.

A composite plot of Hf isotopic compositions for all three of the major components of the Alaska Range suture zone is shown in Figure 10. Utilizing the framework from Bahlburg et al. (2011) and Gehrels and Pecha (2014), epsilon $\text{Hf}_{(t)}$ values that are within 5 units of the depleted mantle (DM) are referred to as compositionally “juvenile”, “intermediate” values range between 5 and 12 units below DM, and “evolved” values are recognized as more than 12 units below DM. Following the approach of Kemp et al. (2009), we interpret evolved (negative) epsilon $\text{Hf}_{(t)}$ values to correspond to input of highly evolved (older) continental crust during melting events related to crustal thickening by magmatic processes. Conversely, juvenile (positive) epsilon $\text{Hf}_{(t)}$ values are interpreted to represent juvenile mantle-derived sources (e.g., Bahlburg et al., 2011; Kemp et al., 2009). The term “vertical arrays” refers to a detrital zircon population with similar ages but varying Hf isotope compositions (vertical color bands in Figure 10). We interpret vertical arrays to signify mixing

Figure 9. Histogram plots of detrital zircon ages from Jurassic-Cretaceous strata of the Kahiltna assemblage in the Alaska Range and northwestern Talkeetna Mountains. The distribution of detrital zircon ages ($n = 1,326$) range between Precambrian-Mesozoic ages, with an abundance of Mesozoic ages ($pC = 30\%$, $pZ = 17\%$, $Mz = 53\%$). The area under the green curve represents the relative probability functions of detrital zircon ages. Samples are grouped by geographic location with the youngest maximum depositional age (MDA) at the top.

of juvenile magmas (e.g., mantle-derived material) with evolved (older) continental crust material; this “mixed” melting event yields a range of Hf isotope compositions for detrital zircons of similar ages.

4. U-Pb Ages and Hf Isotopic Results

U-Pb ages ($n = 3,206$) and Hf isotope compositions ($n = 406$) of 13 analyzed samples are presented from: Ancestral North American margin (samples GC-052805-01, 081115KR-01, 073115KR-01, 16MR18) (Figure 7), Wrangellia terrane (samples 081315KR-02, 072709KR-02, and GR-071702) (Figure 8), and Kahiltna assemblage (samples LC1-CHUL, BC3-792, RG1-146, OC1-630, EFC-071102-04, and TCB-205) (Figure 9). We combine new U-Pb geochronologic data of detrital zircons from the Kahiltna assemblage with previously published U-Pb detrital zircon data from samples BC3-792, RG1-146, OC1-630, EFC-071102-04, and TCB-205 of Hampton et al. (2007, 2010). Additional U-Pb analyses were conducted on samples RG1-146, BC3-792, and OC1-630 to acquire larger n values because U-Pb analyses of the Kahiltna assemblage in the Alaska Range were not as well represented as U-Pb analyses from the Kahiltna assemblage in the Talkeetna Mountains in the study of Hampton et al. (2010). The stratigraphic locations for samples

Figure 10. U-Pb and Hf isotope compositions of detrital zircons from the Ancestral North American margin, Wrangellia terrane, and Kahiltina assemblage samples. (A) Epsilon Hf values for detrital zircon analyses. (B) Normalized age-distribution diagrams for detrital zircons. The average uncertainty of analyses from this study is 2.4 epsilon units (at 2σ). Black arrow represents the average crustal evolution trajectory assuming present-day $^{176}\text{Lu}/^{177}\text{Hf} = 0.0115$ (Vervoort et al., 1999; Vervoort & Patchett, 1996). DM = depleted mantle (Vervoort & Blichert-Toft, 1999), CHUR = chondritic uniform reservoir (Bouvier et al., 2008). Cret = Cretaceous, Jur = Jurassic, Tri = Triassic, Perm = Permian, Penn = Pennsylvanian, Miss = Mississippian, Dev = Devonian, Sil = Silurian, Ordo = Ordovician, Camb = Cambrian.

BC3-792, RG1-146, OC1-630, EFC-071102-04, and TCB-205 are discussed in Hampton et al. (2010). Table 1 lists the locations for all samples in this study along with the type of analyses completed. Table 2 summarizes the detrital zircon U-Pb population ages and ranges of Hf isotope values for all samples in this study. Complete U-Pb geochronologic and Hf isotopic data from all samples analyzed for this study are available in Tables S2 and S3.

4.1. Ancestral North American Margin

Sample 16MR18 from the Healy schist (Figure 5 and Table 1) records Archean and Paleoproterozoic ages with a prevailing peak age at 1838 Ma and a subordinate peak age at 2681 Ma (Figure 7 and Table 2). Subsidiary zircon populations include peak ages at 2595, 2091, 1429, and 1072 Ma. Detrital zircon ages ($n = 289$) from this sample are exclusively Precambrian (pC) in age (pC = 100%). Hf isotope analyses were not conducted for this sample.

Sample 073115KR-01 from the Healy schist (Figure 5 and Table 1) displays 76% of U-Pb age analyses as Archean and Paleoproterozoic ages with peaks at 2708, 1978, and 1840 Ma (Figure 7 and Table 2). Subsidiary Mesoproterozoic zircon populations contain peak ages at 1156 and 1026 Ma. Detrital zircon ages from this sample ($n = 253$) range from Precambrian (pC)-Paleozoic (Pz), with Precambrian (pC) age grains as the most abundant (pC = 99%, Pz = 1%). Epsilon Hf_{t} ratios of Mesoproterozoic zircon ages are almost entirely intermediate, ranging from +8 to −6 (Figure 10). Paleoproterozoic zircon ages display juvenile to evolved epsilon Hf_{t} values that range from +10 to −8. The epsilon Hf_{t} ratios of the Archean zircons are predominantly juvenile, with values ranging from +5 to −2.

Sample 081115KR-01, from the Jarvis Creek Glacier subterrane of the Healy schist (Nokleberg et al., 1992) (Figure 5 and Table 1), records a detrital zircon U-Pb age distribution ($n = 310$) that ranges from Precambrian (pC)-Paleozoic (Pz), with Paleozoic (Pz) ages as the most abundant (pC = 2%, Pz = 98%).

Table 1
Locations of Detrital Zircon Samples From South-Central Alaska

Sample	Formation/assemblage unit	Figure 4 ^a	Latitude (°N) ^b	Longitude (°W) ^b	Analysis
16MR18	Healy schist	7	63.740050	148.889330	DZ U-Pb
073115KR-01	Healy schist	8	63.852933	148.843150	DZ U-Pb and Hf
081115KR-01	Yukon-Tanana terrane ^c	10	63.613900	145.864490	DZ U-Pb and Hf
GC-052805-01	Wood River assemblage	9	63.747632	148.068307	DZ U-Pb and Hf
GR-071702	Unnamed formation below Nikolai basalt	13	62.626812	148.535882	DZ U-Pb and Hf
072709KR-02	Slana Spur formation	12	63.186964	145.129470	DZ U-Pb and Hf
081315KR-02	Slana Spur formation	11	63.329830	145.730850	DZ U-Pb and Hf
TCB-205	Kahiltna assemblage	6	63.204567	149.128533	DZ U-Pb and Hf
EFC-071102-04	Kahiltna assemblage	5	63.169683	149.227967	DZ U-Pb and Hf
OC1-630	Kahiltna assemblage	3	63.076757	149.794050	DZ U-Pb and Hf
LC1-CHUL	Kahiltna assemblage	4	63.108682	149.617211	DZ U-Pb and Hf
BC3-792	Kahiltna assemblage	1	62.261939	153.344898	DZ U-Pb and Hf
RG1-146	Kahiltna assemblage	2	62.776787	150.440819	DZ U-Pb

^aSample location in Figure 4. ^bLatitudes and longitudes reported in decimal degrees, WGS84 projection. ^cJarvis Creek Glacier subterrane of the Yukon-Tanana terrane of Nokleberg et al. (1992).

This sample displays a unimodal distribution with a Late Devonian peak age at 368 Ma (Figure 7 and Table 2). Late Devonian zircon ages cluster with highly evolved epsilon Hf_(t) values between −16 and −20 (Figure 10).

Sample GC-052805-01 from the Wood River assemblage (Figure 5 and Table 1) yields a detrital zircon U-Pb age distribution (n = 287) that ranges from Precambrian (pC)-Mesozoic (Mz), with Precambrian (pC) ages as the most copious (pC = 89%, Pz = 10%, Mz = 1%). Precambrian peak ages occur at 2716, 1913, 1629, 1078, and 543 Ma (Figure 7 and Table 2). Additional significant populations encompass Paleozoic ages such as Silurian and Late Devonian detrital zircon ages (peaks at 439 and 377 Ma, respectively). Epsilon Hf_(t) ratios of Paleozoic grains span from juvenile to evolved, with values between +10 and −7 (Figure 10). Mesoproterozoic zircon ages have juvenile to evolved epsilon Hf_(t) values between +8 and −3 (Figure 10). Paleoproterozoic zircon grains are intermediate to evolved and exhibit epsilon Hf_(t) values between +5 and −9 (Figure 10). The epsilon Hf_(t) ratios of the Archean grains are evolved with values between 0 and −13 (Figure 10).

Table 2
Summary of Detrital Zircon U-Pb Population Ages and Ranges of Hf Isotope Values in South-Central Alaska

Sample	Formation/assemblage unit	Analysis	Detrital zircon U-Pb population ages (Ma)	Range of detrital zircon epsilon Hf _(t) values
Ancestral North American margin				
16MR18	Healy schist	DZ U-Pb	1072, 1429, 1838, 2091, 2595, 2681	X
073115KR-01	Healy schist	DZ U-Pb and Hf	1026, 1156, 1840, 1978, 2708	+10 to −8
081115KR-01	Yukon-Tanana terrane	DZ U-Pb and Hf	368	−16 to −20
GC-052805-01	Wood River assemblage	DZ U-Pb and Hf	377, 439, 543, 1078, 1629, 1913, 2716	+10 to −13
Wrangellia terrane				
GR-071702	Unnamed formation below Nikolai basalt	DZ U-Pb and Hf	322	+16 to +10
072709KR-02	Slana Spur formation	DZ U-Pb and Hf	306	+15 to +11
081315KR-02	Slana Spur formation	DZ U-Pb and Hf	305	+16 to +12
Kahiltna assemblage (Alaska Range and northwestern Talkeetna Mountains)				
TCB-205	Kahiltna assemblage	DZ U-Pb and Hf	124, 203, 386	+14 to −17
EFC-071102-04	Kahiltna assemblage	DZ U-Pb and Hf	115, 194, 338	+13 to −15
OC1-630	Kahiltna assemblage	DZ U-Pb and Hf	112, 127, 201, 363, 1821	+14 to −17
LC1-CHUL	Kahiltna assemblage	DZ U-Pb and Hf	100, 196, 349, 593, 1040, 1163	+13 to −17
BC3-792	Kahiltna assemblage	DZ U-Pb and Hf	99, 203, 354, 1043, 1841	+12 to −17
RG1-146	Kahiltna assemblage	DZ U-Pb	98, 364, 1846, 1979, 2680	X

4.2. Wrangellia Terrane

Sample GR-071702, from an unnamed unit below the Nikolai Greenstone (Figure 5 and Table 1), yields U-Pb detrital zircon ages ($n = 321$) that range from Precambrian (pC)-Cenozoic (Cz), with Paleozoic (Pz) ages as the most abundant (pC = 3%, Pz = 95%, Mz = 1%, Cz = 1%). U-Pb analyses display a dominant population containing a Pennsylvanian peak age at 322 Ma (Figure 8 and Table 2). The epsilon $Hf_{(t)}$ ratios of the Pennsylvanian zircons are entirely juvenile, with values between +16 and +10 (Figure 10).

Sample 072709KR-02 from the Slana Spur formation (Figure 5 and Table 1) records a detrital zircon U-Pb age distribution ($n = 105$) that ranges from Precambrian (pC)-Paleozoic (Pz), with Paleozoic (Pz) ages as the most abundant (pC = 1%, Pz = 99%). This sample displays a unimodal Pennsylvanian peak age of 306 Ma (Figure 8 and Table 2). The epsilon $Hf_{(t)}$ ratios of the Pennsylvanian grains are solely juvenile with values between +15 and +11 (Figure 10).

Sample 081315KR-02 ($n = 315$) from the Slana Spur formation (Figure 5 and Table 1) includes a range of Paleozoic (Pz)-Mesozoic (Mz) ages (Pz = 99%, 1% = Mz), with a predominant unimodal Pennsylvanian peak age of 305 Ma (Figure 8 and Table 2). The epsilon $Hf_{(t)}$ ratios of the Pennsylvanian zircon grains are exclusively juvenile, with values between +16 and +12 (Figure 10).

4.3. Kahiltna Assemblage (Northwestern Talkeetna Mountains)

Two samples (TCB-205 and EFC-071102-04) (Figure 9) from the Kahiltna assemblage in the northwestern Talkeetna Mountains were originally analyzed by Hampton et al. (2007) for U-Pb geochronology. For this study, samples TCB-205 and EFC-071102-04 were analyzed for Hf isotope compositions only; no additional U-Pb analyses were conducted on these two samples. These samples yield a maximum depositional age of 115 Ma. Sample TCB-205 yields a detrital zircon U-Pb age distribution ($n = 80$) that spans from Precambrian (pC)-Mesozoic (Mz), with an abundance of Mesozoic (Mz) ages (pC = 8%, Pz = 16%, Mz = 76%). Detrital zircon U-Pb signatures contain peak age populations at 386, 203, and 124 Ma (Figure 9 and Table 2). Epsilon $Hf_{(t)}$ ratios associated with the Mesozoic 124 Ma peak age range from juvenile to evolved, with values between +14 and +1 (Figure 10). Mesozoic zircon ages associated with the 203 Ma population display an array of juvenile to evolved epsilon $Hf_{(t)}$ values between +13 and -9 (Figure 10). Hf isotope compositions for the Paleozoic peak age of 386 Ma show evolved epsilon $Hf_{(t)}$ values that range from -5 to -17 (Figure 10). The epsilon $Hf_{(t)}$ value for the analyzed Precambrian zircon grain is juvenile with a value of +5 (Figure 10).

Sample EFC-071102-04 ($n = 99$) includes a range of Precambrian (pC)-Mesozoic (Mz) ages, with Mesozoic (Mz) ages as the most abundant (pC = 4%, Pz = 8%, Mz = 88%). Detrital zircon peak ages include 338, 194, and 115 Ma (Figure 9 and Table 2). Epsilon $Hf_{(t)}$ values associated with the 115 Ma Mesozoic peak age range from juvenile to intermediate, with values between +12 and +4 (Figure 10). An array of epsilon $Hf_{(t)}$ ratios coupled with the Mesozoic 194 Ma peak age range from juvenile to evolved, with values between +13 and -7 (Figure 10). Paleozoic zircon ages of the 338 Ma population display evolved epsilon $Hf_{(t)}$ values between -4 and -15 (Figure 10). Epsilon $Hf_{(t)}$ values for Precambrian zircon ages exhibit intermediate to evolved values between +4 and -1 (Figure 10).

4.4. Kahiltna Assemblage (Alaska Range)

Collectively, four samples (OC1-630, LC1-CHUL, BC3-792, RG1-146) from the Kahiltna assemblage in the Alaska Range are presented in Figure 9. Samples OC1-630, BC3-792, and RG1-146 were originally analyzed using U-Pb geochronology for ~100 detrital zircon grains by Hampton et al. (2010). In this study, we analyzed an additional ~200–300 grains for U-Pb geochronology for each of these samples and completed U-Pb analysis on an additional sample (LC1-CHUL). Samples LC1-CHUL, OC1-630, and BC3-792 were also analyzed for Hf isotope compositions in this study. Collectively, these samples yield a maximum depositional age of 98 Ma. Sample OC1-630 yields detrital zircon U-Pb signatures ($n = 307$) that range from Precambrian (pC)-Mesozoic (Mz), with Mesozoic (Mz) ages as the most common (pC = 13%, Pz = 13%, Mz = 74%). Analyzed detrital zircon ages from this sample display peak ages at 1821, 363, 201, 127, and 112 Ma (Figure 9 and Table 2). Subsidiary zircon populations contain peak ages at 232 and 196 Ma. Epsilon $Hf_{(t)}$ analyses of an Early Cretaceous detrital zircon population, peak age at 127 Ma, display an array of juvenile to evolved values that range from +14 to -17 (Figure 10). Detrital zircon ages associated with the

Mesozoic 201 Ma population display juvenile to evolved epsilon $Hf_{(t)}$ values that span from +13 to −13 (Figure 10). Hf isotope compositions for the Paleozoic peak age of 363 Ma display an array of intermediate to evolved epsilon $Hf_{(t)}$ values that range from +8 to −14 (Figure 10). Epsilon $Hf_{(t)}$ ratios of Precambrian zircon ages associated with the 1821 Ma population plot as intermediate to evolved, with values between +2 and −10 (Figure 10).

Sample LC1-CHUL ($n = 302$) contains Precambrian (pC)-Mesozoic (Mz) peak ages, including 1163, 1040, 593, 349, 196, and 100 Ma (pC = 38%, Pz = 16%, Mz = 46%) (Figure 9 and Table 2). An array of epsilon $Hf_{(t)}$ ratios is associated with the 100 Ma peak age, ranging from juvenile to evolved with values between +12 and −16 (Figure 10). Mesozoic zircon ages of the 196 Ma population display juvenile to evolved epsilon $Hf_{(t)}$ values between +13 and −4 (Figure 10). Hf isotope compositions for the Paleozoic peak age of 349 Ma display evolved epsilon $Hf_{(t)}$ values that range from −2 to −17 (Figure 10). Epsilon $Hf_{(t)}$ values for Precambrian zircon ages exhibit juvenile to evolved values between +9 and −4 (Figure 10).

Sample BC3-792 ($n = 259$) contains Precambrian (pC)-Mesozoic (Mz) peak ages that include 1841, 1043, 354, 203, and 99 Ma (pC = 27%, Pz = 17%, Mz = 56%) (Figure 9 and Table 2). Epsilon $Hf_{(t)}$ ratios associated with the 99 Ma peak age range from intermediate to evolved, with values between +9 and −17 (Figure 10). Mesozoic zircon ages of the 203 Ma population display intermediate to evolved epsilon $Hf_{(t)}$ values between +8 and −10 (Figure 10). Hf isotope compositions for the Paleozoic peak age of 354 Ma display an array of juvenile to evolved epsilon $Hf_{(t)}$ values that range from +10 to −11 (Figure 10). Epsilon $Hf_{(t)}$ values for Precambrian zircon grains range from juvenile to evolved with values between +12 and −9 (Figure 10).

Sample RG1-146 ($n = 279$) yields Precambrian (pC)-Mesozoic (Mz) ages. Detrital zircon age populations include 2680, 1979, 1846, 364, and 98 Ma (pC = 60%, Pz = 27%, Mz = 13%) (Figure 9). Hf isotope analyses were not conducted for this sample.

5. U-Pb Geochronology and Hf Isotope Interpretations: Ancestral North American Margin, Wrangellia Terrane, and Kahiltna Assemblage

5.1. Provenance of the Ancestral North American Margin Samples

Detrital zircons ($n = 1,139$) from the continental margin rocks (samples GC-052805-01, 081115KR-01, 073115KR-01, 16MR18) (Figure 7) consist of a wide range of Precambrian to Mesozoic ages, with an abundance of Precambrian (pC) ages (pC = 71%, Pz = 29%, Mz = <1%). Collectively, dominant peak age populations include 2708, 1913, 1838, 1078, and 368 Ma. We interpret the 2708, 1913, 1838, and 1078 Ma detrital zircon peak age populations to represent sediment derived from reworking of secondary sources across northern Laurentia. We interpret the detrital zircon ages containing a peak age population of 368 Ma to have been derived from primary magmatic sources that intruded into the Ancestral North American margin.

5.1.1. Potential Primary Magmatic Sources

Devonian-Mississippian (419–323 Ma) detrital zircon ages make up 27% of the total population and are most common in samples GC-052805-01 and 081115KR-01 (Figure 7). We interpret these detrital zircons to have been sourced from primary magmatic rocks of the Yukon composite terrane/Intermontane Belt (Figure 1). Specifically, Devonian-Mississippian zircon ages may be attributed to regional magmatic sources such as Middle Devonian-Early Mississippian plutons and metavolcanic rocks of the Yukon composite terrane, specifically the Yukon-Tanana terrane (YT in Figure 1) (Colpron et al., 2006; Nelson et al., 2006; Piercey et al., 2006). The unimodal detrital zircon age distribution (peak age of 368 Ma) in sample 081115KR-01 suggests a local source of sediment that was relatively proximal to the area of deposition (i.e., not a regional watershed with multiple sources of sediment); likely sources are the felsic intrusive and extrusive rocks with documented U-Pb zircon ages of 376–353 Ma that have been reported in the Totatlanika schist (or the equivalent Wood River assemblage) and Healy schist in east-central Alaska (Dusel-Bacon et al., 2004, 2006). Additional potential igneous sources along the western Northern Cordillera, but currently more distal to our study area, include a suite of Late Devonian-Mississippian magmatic sources with zircon ages of 365–320 Ma that correlate with the Quesnellia-Slide Mountain terrane in southwestern Yukon and western British Columbia, along with similar Paleozoic ages from the Stikine terrane of southwestern British Columbia (Figure 1) (Currie, 1994; Greig & Gehrels, 1995; Gunning et al., 1994, 2006; Johnston et al., 1996; Mortensen, 1990).

Figure 11. Comparison of U-Pb/Hf data sets. Detrital zircon samples are from this study, Belousova et al. (2010), and Gehrels and Pecha (2014). (top) Hf isotopic compositions for the associated U-Pb analyses from western North America from Gehrels and Pecha (2014) (red diamonds), modern rivers from various global regions provided by Belousova et al. (2010) (gray symbols), and this study (blue symbols). (bottom) Probability density plots (PDPs) of summarized U-Pb ages from western North America (red PDP), a global data set (gray PDP), and south-central Alaska (blue PDP). DM = depleted mantle, CHUR = chondritic uniform reservoir. Modified from Gehrels and Pecha (2014).

5.1.2. Potential Secondary (Reworked) Sources

Precambrian detrital zircon grains, 71% of the total population, are interpreted to have been derived most likely from secondary sources prior to final deposition in our study area. In our study, 11% of the total population is Grenville-age and we interpret these 1349–952 Ma detrital zircon grains to represent the product of reworking of sediment from older sedimentary and metasedimentary strata across northwestern Laurentia throughout Proterozoic–Paleozoic time. For example, previous studies report Grenville-age detritus that accumulated in continental-scale clastic wedges that are interpreted to have spanned across northwestern Laurentia during the Neoproterozoic (Rainbird et al., 2012). There are other potential sources of the same age range such as the 1000–950 Ma orthogneiss units and their sedimentary derivatives in the Canadian Arctic (Estrada et al., 2018).

Paleoproterozoic (2498–1602 Ma) detrital zircon ages, 37% of the total population in our data set, are interpreted to have been derived from reworking of sediment that included Paleoproterozoic (2500–1600 Ma) magmatic sources that occur throughout northern Laurentia. Specifically, Paleoproterozoic ages ranging between 2.0 and 1.8 Ga are likely derived from reworked sediment of recognized magmatic arcs such as the Fort Simpson (1845 Ma) and Great Bear (1865–1840 Ma) in western Canada (Figure 11 in Linde et al., 2017). Archean detrital zircon ages from our data set, 16% of the total population, are similar to ages reported from the Archean provinces in North America (e.g., Wyoming, Hearn, Slave, Nova, Rae, and Superior cratons) (e.g., Bickford et al., 1986; Hoffman, 1989; Ross, 1991; Van Schmus et al., 1993). Specifically, the Superior craton contains a range of Archean metasedimentary strata with a distinguishing peak age at approximately 2.7 Ga (Cawood & Nemchin, 2001) and may be the source of the 2716, 2708, and 2681 Ma peak age populations in our samples (Figure 7).

5.2. Ancestral North American Margin Hf Isotopic Data Interpretation

Our Hf isotopic data from the Ancestral North American margin samples show four major stages of crustal melting recorded in the detrital zircons. Archean zircon ages from our samples, specifically Neoarchean (2800–2500 Ma), display epsilon $Hf_{(t)}$ ratios in a vertical array that represent a mixing event which incorporated juvenile magmas with older crustal material (Figure 10). During the Paleoproterozoic, specifically between 2000 and 1800 Ma, zircon signatures may be a product of two events: (1) recycling of older crustal material (Archean) as shown by the highly evolved (negative) epsilon $Hf_{(t)}$ ratios and (2) mixing of juvenile magmas with older continental crust as expressed by a vertical array of epsilon $Hf_{(t)}$ values. Mesoproterozoic zircon ages, particularly between 1200 and 1000 Ma, display epsilon $Hf_{(t)}$ values in a vertical array, suggesting a mixing event of juvenile magmas with older crust. Following the trajectory path of the crustal evolution arrow shown in Figure 10, it is possible for there to have been a slight component of older crustal material (Paleoproterozoic) that was recycled during zircon production between 1200 and 1000 Ma. During the mid-Paleozoic, specifically between 400 and 335 Ma, zircon production resulted from (1) mixing of juvenile magmas with older crustal components and (2) recycling of older crustal material (Mesoproterozoic), based on the vertical array and the crustal evolution trajectory path (Figure 10). Clustering of highly evolved (negative) epsilon $Hf_{(t)}$ values associated with Late Devonian zircon ages strongly indicates melting of older crust (Paleoproterozoic–Mesoproterozoic) with no influence from juvenile sources (red diamonds in Figure 10). The most highly evolved values are mainly from sample 081115KR-01 that, as discussed earlier, we interpret as being sourced from Upper Devonian–Lower Mississippian igneous rocks that intruded into the Yukon composite terrane.

5.3. Provenance of the Wrangellia Terrane

Detrital zircons ($n = 741$) from the Wrangellia terrane (samples 081315KR-02, 072709KR-02, GR-071702) consist predominantly of Paleozoic (Pz) ages with very minor Precambrian, Mesozoic, and Cenozoic ages ($pC = 1\%$, $Pz = 98\%$, $Mz = 1\%$, $Cz = <1\%$) (Figure 8). Collectively, detrital zircons display a unimodal population with a peak age of ~ 310 Ma (Figure 8).

5.3.1. Potential Primary Magmatic Sources

Early Mississippian–Early Permian (357–290 Ma) detrital zircons, 98% of the total population, are likely derived from nearby plutonic rocks of the Wrangellia terrane. The unimodal distribution of ages in these samples suggests more local watersheds with a single monolithic source area. Possible plutonic sources are likely those associated with Paleozoic arcs that form the lower part of the Wrangellia terrane in eastern Alaska and southwestern Yukon (Figure 5).

Two of our samples are from the Slana Spur formation. This formation is the stratigraphic equivalent of the Station Creek formation that contains a felsic tuff that has a published age of 353.8 Ma (Israel et al., 2014). Specific potential late Paleozoic sources include the Pennsylvanian–Permian (320–290 Ma) plutonic suites related to the Skolai arc and the equivalent Strelina metamorphic rocks that have been reported from the Wrangellia terrane in southern Alaska (Plafker et al., 1989, and references therein). Skolai arc intrusions have ages concentrated between 310 and 305 Ma (Beard & Barker, 1989). Other late Paleozoic plutonic suites containing potential sources for the Wrangellia terrane detritus include the Middle to Late Pennsylvanian (307–301 Ma) Barnard Glacier suite and the Early Permian (291–284 Ma) Donjek Glacier suite in eastern Alaska and southwestern Yukon (Beranek et al., 2014, and references therein). All of these plutons are part of a suite of Pennsylvanian and Lower Permian igneous rocks exposed throughout the Wrangellia and Alexander terranes in eastern Alaska and southwestern Yukon and are the interpreted sources of sediment for our samples. We interpret the Mississippian–Early Permian (357–290 Ma) detrital zircon ages in our data, 98% of the total population, to have been predominantly derived from magmatic sources of similar ages in the Wrangellia and Alexander terranes.

5.3.2. Potential Secondary (Reworked) Sources

Contributions from secondary sources of sediment appear to be minor on the Wrangellia terrane based on our limited samples. Potential sources for Precambrian ages, 1% of the total population, may have been secondary sources from the Alexander terrane, part of the Wrangellia composite terrane of Plafker et al. (1994).

5.4. Wrangellia Terrane Hf Isotopic Data Interpretation

Epsilon $Hf_{(t)}$ ratios ($n = 68$) of the Wrangellia terrane are entirely juvenile with values between +16 and +10 (blue symbols in Figure 10). The highly positive epsilon $Hf_{(t)}$ values indicate that Late Paleozoic magmatic sources of the Wrangellia terrane experienced very little continental crustal input. We interpret the highly positive Hf isotopic signature of these detrital zircons to indicate that the lower part of the Wrangellia terrane exposed in south-central Alaska developed within a Late Paleozoic juvenile arc system. Our interpretation is consistent with the interpretations of Nokleberg et al. (1985), Beard and Barker (1989), and Israel et al. (2014) in that the Slana Spur formation and the equivalent Station Creek formation of the Wrangellia terrane represent part of an oceanic arc system.

5.5. Provenance of the Kahiltna Assemblage

Detrital zircons ($n = 1,326$) from the Kahiltna assemblage entail an assortment of Precambrian to Mesozoic ages, with a dominance of Mesozoic (Mz) grains ($pC = 30\%$, $Pz = 17\%$, $Mz = 53\%$). Specific potential primary and secondary sources for Late Paleozoic-Mesozoic detrital zircons are discussed in the following section. The following section does not, for the sake of length, however, go into detail on potential sources of sediment already described for the Ancestral North American margin and the Wrangellia terrane.

5.5.1. Potential Late Paleozoic-Mesozoic Primary Magmatic Sources: Yukon Composite Terrane/Intermontane Belt

Permian-early Late Cretaceous (298–85 Ma) detrital zircon ages make up 55% of the total population for the Kahiltna assemblage. Triassic-Late Jurassic (250–145 Ma) detrital zircon grains, 41% of the total population, may have been derived from primary magmatic sources associated with the Intermontane Belt terranes such as the Cache Creek, Quesnellia-Slide Mountain, and Stikinia in the Yukon and British Columbia (Figure 1), all of which contain Middle Triassic-Late Jurassic (245–145 Ma) igneous rocks (summarized in Hampton et al., 2010). The 203, 201, 196, and 194 Ma peak ages in the Kahiltna samples (Figure 9) match well with published ages from plutonic rocks of the Klotassin Suite of the Stikine terrane in the Yukon (U-Pb zircon age of 192 Ma; Tempelman-Kluit & Wanless, 1980), the Taylor Mountain batholith (Figure 4) of the Yukon composite terrane in east-central Alaska (U-Pb zircon ages of 216–181 Ma; Day et al., 2014; Dusel-Bacon & Murphy, 2001; Dusel-Bacon et al., 2009), and other Late Triassic-Early Jurassic age igneous rocks (215–175 Ma) in east-central Alaska (e.g., Aleinikoff et al., 1981; Dusel-Bacon et al., 2002; Foster et al., 1994; Wilson et al., 1985). Additional potential sources include three suites of Late Triassic-Early Jurassic plutons within the Yukon composite terrane, along with the northern segments of the Stikinia and Quesnellia terranes, in southwestern Yukon (Colpron, 2015; Gordey & Makepeace, 2001). Specifically, the 220–206 Ma, 204–195 Ma, and 190–178 Ma plutonic suites are located in south-central Yukon, near the Whitehorse trough (Colpron, 2011; Hart et al., 1995; Hart & Radloff, 1990). A less widespread suite of 174–168 Ma plutonic rocks has also been reported in southern Yukon and may also have served as a potential magmatic source (e.g., Hart et al., 1995).

Cretaceous (145–85 Ma) detrital zircon grains, 12% of the total population, may have been derived from Early and mid-Cretaceous (145–90 Ma) magmatic sources that are widespread throughout eastern Alaska and the Yukon (Figure 1). Potential Early and mid-Cretaceous magmatic sources include plutons of the Yukon composite terrane in east-central Alaska; reported U-Pb zircon ages for these plutonic rocks are between 109–102 Ma (Day et al., 2003; Dilworth et al., 2002; Smith et al., 1999, 2000; Weldon et al., 2004). Mid-Cretaceous (~105–85 Ma) K-Ar and Ar-Ar ages from granitic plutons have been reported to intrude regions north, west, and south of the Taylor Mountain batholith (Dusel-Bacon et al., 1995; Wilson et al., 1985). A potential mid-Cretaceous magmatic source in the Yukon includes the Whitehorse plutonic suite with documented U-Pb ages of 115 Ma and 111 Ma (Hart, 1997). More distal potential sources, relative to the present position of the study area, include Jurassic-Paleogene plutons of the Coast Mountains batholith (Figure 1) that range in age from 160–50 Ma (Gehrels et al., 2009, and references therein).

5.5.2. Potential Secondary (Reworked) Sources: Yukon Composite Terrane/Intermontane Belt

Jurassic and older detrital zircon ages, 88% of the total population, may have also been derived from secondary sources prior to deposition in the Kahiltna basin. Sediment may have been reworked from regional secondary sources such as Mesozoic and older sedimentary strata in the northwestern Cordillera. In the Yukon, for example, the Whitehorse trough contains Upper Triassic and Lower to Middle Jurassic sedimentary strata that overlie terranes of the Intermontane Belt (Wheeler, 1961). Jurassic strata of equivalency have

been documented in multiple locations in the southern Yukon (i.e., youngest strata in the Cache Creek terrane, Faro Peak formation in central Yukon, and Macauley Ridge formation in western Yukon; Colpron et al., 2015, and references therein). Colpron et al. (2015) also reported that detrital zircon analyses from the Whitehorse trough contain Late Triassic-Early Jurassic (220–180 Ma) and mid-Paleozoic (340–330 Ma) dominant age distributions. Similarly, detrital zircons from the Kahiltina assemblage in south-central Alaska contain dominant peak age populations of 363, 201, and 178 Ma (Figure 9). Overlapping of similar Triassic and Jurassic detrital zircon ages may suggest the following: (1) similar Triassic and Jurassic magmatic suites sourced the Kahiltina assemblage and Whitehorse trough and/or (2) Triassic and Jurassic (and older) detrital zircons present in the Kahiltina assemblage may have been sourced by erosion of exhumed strata from the Whitehorse trough, or similar sedimentary basins during the Cretaceous (e.g., Colpron et al., 2015).

5.5.3. Potential Paleozoic-Mesozoic Magmatic Sources: Wrangellia Composite Terrane

Devonian-Cretaceous (416–85 Ma) detrital zircon ages, 68% of the total population of the Kahiltina assemblage, may have also been sourced by plutons within the Wrangellia composite terrane that were located south of the Kahiltina basin (in present coordinates). For example, Devonian-Permian (416–253 Ma) detrital zircon ages, 15% of the total population, may have been derived from known plutonic rocks of the Wrangellia composite terrane. Potential sources for Devonian zircons include a gabbroic suite with a Late Devonian age of 363 Ma from the Wrangellia and Alexander terranes in the Yukon (Israel et al., 2014) and Devonian igneous rocks from the Sicker Group of the Wrangellia terrane at Vancouver Island (Ruks et al., 2009, 2010, and references therein).

An important observation in distinguishing between Wrangellia versus inboard continental terranes is the lack of overlap between our samples from the Pennsylvanian-Permian Slana Spur formation of Wrangellia and the Kahiltina assemblage as shown on the normalized distribution plots in Figure 10. This observation minimizes the likelihood of Paleozoic age plutonic rocks that form the lower part of the Wrangellia composite terrane (i.e., the Skolai arc) to have been a major contributing source of sediment for the Kahiltina assemblage. Overlying the Skolai Group are ~3 km of mafic basalt of the Triassic Nikolai Greenstone and ~2 km of mainly limestone and mudstone of the Triassic-Jurassic Chitistone Limestone, Nizina Limestone, McCarthy Formation, and Lubbe Creek Formation (Armstrong et al., 1969; MacKevett, 1969; Trop et al., 2002). The zircon fertility (e.g., Dickinson, 2008; Moecher & Samson, 2006) of these strata is unknown and needs to be tested but based on lithologies they are probably not conducive to generating abundant zircon-rich sediment. A better indicator of Wrangellia sources of sediment are the Mesozoic plutons that intrude it and are discussed in the following text.

Late Triassic-Late Jurassic detrital zircon ages (201–145), 23% of the total population, may have been derived from magmatic sources associated with the Talkeetna arc (201–153 Ma) of the Peninsular terrane in southwestern and south-central Alaska. Talkeetna arc magmatism had major magmatic pulses between 201–181 Ma and 177–153 Ma (Amato et al., 2007; Rioux et al., 2007, 2010). Farther southeastward along strike, arc-related plutons have U-Pb zircon ages between 155–147 Ma (Beranek et al., 2017). Rocks of similar age and lithology, called the Bonanza arc (202–160 Ma) of the Wrangellia terrane, are located in southwestern British Columbia (DeBari et al., 1999). It is important to note the overlap between potential magmatic source ages of both the Talkeetna arc (201–153 Ma) and Late Triassic to Early Jurassic plutonic suites of the Yukon-Tanana, Stikinia, and Quesnellia terranes (204–195 Ma, 190–178 Ma, and 174–168 Ma). However, the presence of considerable Triassic detrital zircon ages that are older than plutons of the Talkeetna arc supports the likelihood of plutonic rocks from the Intermontane Belt to have been a more likely major contributing source for the Late Triassic-Late Jurassic detrital zircons in the Kahiltina assemblage.

Middle Jurassic-middle Cretaceous (175–115 Ma) detrital zircon ages, 11% of the total population, may have been derived from magmatic sources associated with the Middle Jurassic-Early Cretaceous Chitina (175–135 Ma) and the Early Cretaceous Chisana arcs (140–115 Ma) (Nokleberg et al., 1994; Plafker et al., 1989; Roeske et al., 2003; Snyder & Hart, 2007). Along strike in the Wrangell Mountains, Late Jurassic-Early Cretaceous plutons of the Chitina arc have 153–150 Ma U-Pb zircon ages (Plafker et al., 1989; Roeske et al., 1992, 2003). U-Pb zircon ages of modern river sands draining the Chitina Valley batholith, however, range between 156–130 Ma (Day et al., 2016; Trop et al., 2016). Jurassic-Cretaceous detrital zircon ages, 4% of the total population, fall within the age range associated with the Chitina arc (175–135 Ma), whereas Cretaceous detrital zircon ages, 7% of the total population, fall within the age range associated with the

Chisana arc (140–115 Ma) (Plafker et al., 1989; Snyder & Hart, 2007). The peak ages of 127 Ma (sample OC1-630 in Figure 9), 124 Ma (sample TCB-205 in Figure 9), and 115 Ma (sample EFC-071102-04 in Figure 9) may be indicative of some small sediment contribution from the Chisana arc located on the Wrangellia terrane. Plutons of this age are rare in the northern Cordillera and, to our knowledge, the only reported plutons of this age that are from the Chisana arc that are well exposed in the Wrangell and Nutzotin Mountains of eastern Alaska. In this area, recently published U-Pb zircon ages from these plutons, called the White Mountain granitoid belt, are from 126–117 Ma (Graham et al., 2016). The overlap in ages between detrital zircons of the Kahiltna assemblage and the plutons of the Chisana arc appear to be evidence for some sediment contribution from Wrangellia as first pointed out by Hampton et al. (2010).

Other potential middle-late Paleozoic magmatic sources of sediment for the Kahiltna assemblage from the outboard oceanic terranes include Ordovician-Devonian (480–410 Ma) and Permian-Triassic (280–220 Ma) plutons that have been documented in the Alexander terrane (e.g., Gehrels, 1990; Gehrels & Saleeby, 1987). The 500–400 Ma detrital zircons are rare throughout the northern Cordillera but are diagnostic of the Alexander terrane (Gehrels et al., 1996; Grove et al., 2008). The presence of small amounts of these zircons in the Kahiltna assemblage (Figure 12A) suggests that some minor sediment may have been derived or reworked from this terrane.

5.6. Kahiltna Assemblage Hf Isotopic Data Interpretation

Detrital zircon samples from the Kahiltna assemblage exhibit three distinct age populations: one Paleozoic (Devonian-Mississippian) and two Mesozoic (Late Triassic-Early Jurassic; Early Cretaceous-Late Cretaceous) as shown in Figure 10. The Devonian-Mississippian age population displays juvenile to evolved epsilon $Hf_{(t)}$ ratios (+10 to −17) in a vertical array (Figure 10). The detrital zircon age population represented by Late Triassic-Early Jurassic ages show juvenile to evolved epsilon $Hf_{(t)}$ ratios (+13 to −13) in a vertical array (Figure 10). The Early Cretaceous-Late Cretaceous age population also displays juvenile to evolved epsilon $Hf_{(t)}$ ratios (+14 to −17) in a vertical array (Figure 10).

We interpret each of these vertical arrays to represent a stage of crustal growth by magmatic thickening, each stage documenting when juvenile magmas assimilated older continental crust material. The Early Cretaceous-Late Cretaceous detrital zircon ages can be further separated, containing two peak ages at 122 Ma and 98 Ma. Detrital zircon ages ranging from 142–107 Ma (peak age of 122 Ma) display juvenile to evolved epsilon $Hf_{(t)}$ values (+14 to −17), with dominant intermediate and juvenile Hf isotope compositions. Detrital zircon ages ranging from 106–85 Ma (peak age of 98 Ma) show evolved epsilon $Hf_{(t)}$ ratios (+1 to −16). Our Hf isotopic data set from the Kahiltna assemblage (Figure 10) records three stages of crustal growth along the northwestern Laurentia margin during the Phanerozoic; these events occurred during Devonian-Mississippian, Late Triassic-Early Jurassic, and Early Cretaceous-Late Cretaceous. To our knowledge, these are the first reported $Hf_{(t)}$ ratios reported from the Kahiltna assemblage.

6. Discussion

6.1. Implications for Global and Cordilleran Tectonics

In this study, we utilize the relatively new approach of combining U-Pb geochronology and Hf isotope geochemistry of detrital zircons to better unravel tectonic and magmatic processes along the northwestern Cordilleran margin. Our U-Pb/Hf data sets from the Alaska Range suture zone also contribute to the growing database of global melting events (Figure 11) (e.g., Belousova et al., 2010; Gehrels & Pecha, 2014). Our analysis defines specific time intervals when detrital zircons have a wide range of epsilon $Hf_{(t)}$ ratios as shown in Figure 10. We refer to these wide ranges as vertical arrays and interpret these time intervals to represent distinct episodes of juvenile magmas assimilating older continental crust following the framework of Kemp et al. (2009), Gehrels and Pecha (2014), Ducea et al. (2015), and Pecha et al. (2016). In this section, we integrate our new data with previous geological studies from southern Alaska to show that these vertical arrays developed during times of compressional deformation and magmatic thickening of the crust. In the Alaska Range suture zone, these episodes can be correlated to Archean and Proterozoic stages of global crustal growth, and to Phanerozoic intervals of more regional collisional-related magmatism and other magma/crust interactions within the evolving Cordilleran convergent margin.

Our samples from the Ancestral North American margin rocks of the Alaska Range suture zone have major populations at 2800–2600 Ma, 2000–1800 Ma, and 1200–1000 Ma and are consistent with Hf signatures from western North America that have been interpreted by previous studies as representing Archean and Proterozoic global tectonic events documented across Laurentia (Figure 11) (e.g., Cawood et al., 2013; Condie et al., 2011; Gehrels & Pecha, 2014; Hawkesworth et al., 2010; Roberts, 2012). These include stages of crustal melting during the Archean and Proterozoic that in some cases can be correlated with crustal growth during the assembly of the supercontinents (Figure 11) (e.g., Linde et al., 2017; Thomas et al., 2017). Building on these previous studies, our data suggest a significant juvenile component of melting during Archean crustal growth (2800–2600 Ma in Figure 11). The next cluster in the data set from the Alaska Range suture zone is the vertical array between 2000–1800 Ma in Figure 11. This cluster is consistent with Paleoproterozoic reworking of Archean crust during a major episode of crustal growth in western North America and throughout Laurentia. Our data show some presence of 1500–1400 Ma detrital zircons with mainly intermediate Hf signatures (Figure 11) but we did not document the large population with juvenile signatures as shown by Gehrels and Pecha (2014) for all of western North America during this time range. This may be a function of this melting event being more geographically restricted to the southwestern North American Cordillera (e.g., Aronoff et al., 2016; Bickford et al., 2008; Jones et al., 2011; Wooden et al., 2013). The cluster of data between 1200 and 1000 Ma in the Alaska Range suture zone is interpreted as a product of the growth of the Rodinia supercontinent (see earlier cited references). The large gap in detrital zircons between 1000–600 Ma in Figure 11 is interpreted to represent the non-magmatic, tectonic development of the Cordillera passive margin and is consistent with the western North America database as shown in Figure 11 (e.g., Dickinson, 2004; Sloss, 1988). These general correlations are consistent with our interpretation that much of the detritus in the Alaska Range suture zone was first derived from primary Laurentian sources and probably reworked multiple times prior to deposition along the northwestern continental margin.

On a more regional Cordilleran scale, U-Pb and Hf isotope analyses from detrital zircons in the Kahiltina assemblage record several Phanerozoic crustal melting events (Figure 11). Devonian-Mississippian detrital zircon ages from the Ancestral North American margin and Kahiltina assemblage samples, for example, display juvenile to evolved epsilon $Hf_{(t)}$ ratios (+10 to –20) in a vertical array (gold swath in Figure 10). We interpret this Paleozoic vertical array to represent a major phase of Devonian-Mississippian magmatic thickening, documenting when juvenile magmas assimilated older continental crustal material. Previous studies have shown that Devonian-Mississippian rocks encapsulate a period that is characterized as a stage of major arc building along the entire Cordilleran margin, with northern Cordilleran regions marked by compressional deformation, granitic plutonism, andesitic to felsic volcanism, and coarse clastic sedimentation (see review by Plafker & Berg, 1994). Previous studies of the Yukon composite terrane, for example, indicate that during the Late Devonian to Mississippian (365–342 Ma), this terrane was characterized by abundant felsic magmatism of crustal affinity, and evolved epsilon $Hf_{(t)}$ values in these rocks have been interpreted to record crustal thickening (Dusel-Bacon et al., 2006; Nelson et al., 2006; Pecha et al., 2016). Our U-Pb geochronology and Hf geochemistry of detrital zircons from the Alaska Range suture zone are consistent with these previous studies.

A second distinct Phanerozoic event in our data are the Early Mississippian–Early Permian detrital zircon ages from the Wrangellia terrane samples that display entirely juvenile epsilon $Hf_{(t)}$ ratios (+16 to +10; blue symbols in Figure 10). These highly juvenile values indicate that these detrital zircons must have been produced primarily from melting of mantle material or crustal material that was extracted from the mantle only a short time before magmatic crystallization. We interpret the cluster of late Paleozoic Hf isotope compositions to represent the early stages of development of the Wrangellia terrane within a Mississippian–Permian oceanic arc system (e.g., Skolai arc). Supporting this oceanic interpretation is the minor amount of Precambrian detrital zircons in Pennsylvanian–Permian strata from the Wrangellia terrane ($pC = 3\%$; Figure 8), suggesting a lack of significant sediment derivation from continental sources during deposition. We interpret detrital zircon ages and their $Hf_{(t)}$ isotopic compositions from the Wrangellia terrane samples to have been derived from local magmatic sources of the Mississippian–Permian Skolai oceanic arc system that was outboard of the northern Cordillera with no clear detrital connection to the North America continental margin at that time. The lack of Early Mississippian–Early Permian detrital zircons with juvenile epsilon $Hf_{(t)}$ ratios in the western North America data set (Figure 11) seems consistent with the Wrangellia terrane being a more northern Cordilleran specific event (e.g., Greene et al., 2008; Jones et al., 1977). It is

also interesting to note that the only reported primary sources of zircons of this age in North America are from the Paleozoic plutons (500–310 Ma) exposed along the Laurentian-Gondwana suture zone in the Appalachian orogen (e.g., Dickinson & Gehrels, 2003). The presence of detrital zircons of this age in sedimentary strata of western North America is mostly attributed to transcontinental fluvial systems that provided sediment derived from plutons in eastern North America (Dickinson & Gehrels, 2009; Laskowski et al., 2013). These provenance interpretations seem reasonable in most cases but our data suggest that after collision and incorporation of the Wrangellia terrane into western North America, it may have provided local sources for zircons in this age range.

The first major Mesozoic phase of magmatic thickening in our study area is marked by Late Triassic–Early Jurassic detrital zircon ages from Kahiltna assemblage samples that display juvenile to evolved epsilon $Hf_{(t)}$ ratios (+13 to −13) in a vertical array (orange swath in Figure 10). Previous studies of Upper Triassic–Lower Jurassic rocks of the northern Cordilleran define this time interval as a period of convergence between the Farallon plate and the continental margin (Plafker & Berg, 1994). This convergence produced the Late Triassic–Early Jurassic Quesnellia magmatic arc and its accretionary prism, the Cache Creek terrane along the northwestern Cordilleran margin (Colpron et al., 2015; Miller, 1987; Plafker & Berg, 1994; Saleeby, 1983). In our study area, the vertical array of epsilon $Hf_{(t)}$ ratios for these samples indicate that juvenile magmas mixed with older continental crust material during this stage of tectonic development of the northwestern Cordillera. The Hf reference data set for western North America of Gehrels and Pecha (2014) only extends from Neoproterozoic through Triassic time so how this event documented in the Alaska Range suture zone correlates with the rest of western North America will require additional data sets.

A second Mesozoic stage of crustal melting and magmatic thickening recorded in our data is defined by Early-middle Cretaceous detrital zircon ages from the Kahiltna assemblage samples that display juvenile to evolved epsilon $Hf_{(t)}$ ratios (+14 to −17) in a vertical array (pink swath in Figure 10). Early-middle Cretaceous (Aptian–Campanian) plutonic rocks have been interpreted to represent magmatism in an ~600-km-broad belt that trends in a northwest-southeast orientation throughout southern Alaska and the Canadian Cordillera (Armstrong, 1988; Miller, 1994). This magmatic belt is interpreted to represent continental margin arc magmatism above a shallow, east-dipping subduction zone, and includes plutons that may have formed from crustal melting (Crawford et al., 1987; Hudson, 1994; Miller, 1994; Pavlis et al., 1993). The polarity of the subduction zone during the Late Jurassic–Early Cretaceous remains a controversial topic (e.g., Monger, 2014; Pavlis et al., 2019; Sigloch & Mihalynuk, 2013). We prefer an east-dipping subduction orientation during the Early-middle Cretaceous, which would have resulted in the addition of high-volume magmatism associated with continental arc lithosphere, regional compression, and major crustal thickening related to these processes. This interpretation would be consistent with previous studies that document a mid-Cretaceous ilmenite-series plutonic suite in Alaska and Yukon that is interpreted to represent melting in a compressional setting, likely representing interactive melting of metasedimentary continental crust due to crustal thickening (Hart et al., 2004; Ishihara, 1981).

As discussed in the earlier section entitled “Geophysical and Geologic Configuration of the Alaska Range Suture Zone” and shown in Figures 2 and 3, the surface distribution of the Kahiltna assemblage marks the location of the thickest crust along this collisional zone (~37 km thick; central section in Figure 3). This thicker crust has been interpreted by previous studies to be the product of focused regional shortening, metamorphism, and magmatism (Brennan et al., 2011; Davidson et al., 1992; Jones et al., 1982; Ridgway et al., 2002). Also note that this zone is marked by major steps in the Moho separating this area of crustal thickening from the adjacent rocks of both the Ancestral North American margin (northern section in Figure 3) and oceanic rocks of the Wrangellia terrane (southern section in Figure 3). Our new U–Pb geochronology and Hf geochemistry data delineate two distinct crustal end-members of the suture zone, the highly juvenile Wrangellia terrane with U–Pb ages of 357–290 Ma (blue symbols in Figure 10) and the highly evolved rocks of the Ancestral North American margin with U–Pb ages of 419–323 Ma (red diamond symbols in Figure 10). Within this framework, we interpret the Late Triassic–Early Jurassic and Cretaceous vertical arrays defined by samples from the Kahiltna assemblage (Figure 10) as products of juvenile magmas assimilating these two very different rock types that had been tectonically juxtaposed within this collisional tectonic setting. This study was not designed to specifically address the timing of collision of the Wrangellia composite terrane with the continental margin of western North America but it does provide some new insights that may be useful to future studies addressing this question. The timing of collision is debated

with interpretations ranging from Early Jurassic to Late Cretaceous (e.g., Box et al., 2019; Gehrels et al., 2009; Monger, 2014; Stevens Goddard et al., 2018; Trop et al., 2020; Trop & Ridgway, 2007). Our new data delineate two distinct melting events in the Alaska Range suture zone that may be related to collisional processes. The Late Triassic-Early Jurassic and Early Cretaceous-mid Cretaceous vertical arrays shown in Figure 10 (orange and pink swaths, respectively) are interpreted to represent stages when juvenile magmas were assimilating older continental crust as might be predicted with closing of an ocean basin and/or backarc basin. Additional studies will be required to determine if only one of these stages marks the collision or if there were two discrete stages of collision.

Development of an integrated detrital zircon U-Pb and Hf reference data set for North America is in its early stages and first attempted by Gehrels and Pecha (2014). These authors point out that there are many areas along western North America where there is little or no Hf isotopic information available. Our data from the Alaska Range suture zone are one of the first steps toward developing a database for the northernmost part of the North America Cordillera. Our results show that it is a promising approach for linking tectonic processes at both the global and Cordillera scales.

6.2. Comparison With Along-Strike Jurassic-Cretaceous Basins

In the northwestern American Cordillera, a >2000-km-long, discontinuous belt of Jurassic-Cretaceous marine strata is located between the inboard, continental Ancestral North American margin/Intermontane Belt and the outboard, oceanic Wrangellia composite terrane/Insular Belt (Figure 1). Because of their geologic location, these strata are critical for understanding the Mesozoic geologic development of the northern Cordillera and interpretations have varied for these strata from representing a series of syn-collisional basins (Hampton et al., 2007, 2010; Kalbas et al., 2007; Pavlis, 1982; Ridgway et al., 2002; Wallace et al., 1989), to linked post-collisional backarc basins (Gehrels et al., 2009; Gehrels et al., 2017; McClelland & Mattinson, 2000; Monger, 2014; Yokelson et al., 2015), to a pre-collisional forearc basin setting (Lowey, 2018), and/or to unrelated basins (Hults et al., 2013). In this section, we present an overview of the available detrital zircon geochronologic data from these basins and make a comparison with our new data from the Kahiltina assemblage in south-central Alaska (Figure 12). Our goal here is to point out some of the similarities and differences in detrital records between these basins (Figure 12) that hopefully generates and fosters needed future studies.

The first major difference in the along-strike Jurassic-Cretaceous basins is the large population of Late Triassic-Early Jurassic detrital zircons in the Kahiltina assemblage of the central Alaska Range (Figure 12A), southwestern Alaska Range (Figure 12B), and the northwestern Talkeetna Mountains (Figure 12C), containing peak populations at 201, 200, and 198 Ma. Potential sources for this sediment are the widespread Late Triassic-Early Jurassic plutons and related sedimentary strata of the inboard Intermontane Belt that have been discussed earlier. This population, in combination with the presence of Precambrian grains, provides a strong link to North American continental sources for the Jurassic-Cretaceous basins that contain Kahiltina assemblage in the central Alaska Range, southwestern Alaska Range, and the northwestern Talkeetna Mountains (Figures 12A–12C). Note that the Late Triassic-Early Jurassic detrital zircons are absent in the KA-CM and NMS (Figures 12D and 12E) and present in only small amounts in the DF, WG, and EG basins (Figures 12F–12H).

A second distinct difference in detrital zircon populations is that the Clearwater Mountains (Figure 12D), Nutzotin Mountains sequence (Figure 12E), Dezadeash Formation (Figure 12F), western strata of the Gravina belt (Figure 12G), and eastern strata of the Gravina belt (Figure 12H) each display a dominant Jurassic detrital zircon population which includes peak ages at 158, 156, 155, 152, and 151 Ma. Previous studies have identified potential sources for these zircon grains to have been the Talkeetna arc plutons and Chitina batholith in south-central Alaska, and the Jurassic plutons in the St. Elias Mountains (Beranek et al., 2017; Lowey, 2018). All these potential Jurassic igneous sources have intruded the outboard oceanic terranes and imply a large contribution of sediment from the outboard terranes to the Jurassic-Cretaceous basins. Another potential major source for Jurassic age zircons is the Coast Mountains batholith, located on the crustal boundary between the inboard (continental) and outboard (oceanic) terranes in British Columbia (Figure 1). This batholith had a major magmatic flux between 160 to 140 Ma (Gehrels et al., 2009) and has been interpreted as an important source of sediment for nearby basins such as the eastern Gravina basin (EG in Figure 12H).

Figure 12. Comparison of normalized detrital zircon age distribution diagrams from Jurassic-Cretaceous basinal assemblages in the North American Cordillera that are located along the crustal boundary between oceanic terranes (Wrangellia composite terrane, Insular terrane) and more continental terranes (Yukon composite terrane, Intermontane terrane). The geographic location of each basin is shown in Figure 1. To review the stratigraphy of each basin is beyond the scope of the comparison and we refer the reader to the cited references. Data from (A) this study, Kalbas et al. (2007), Hampton et al. (2010), (B) Hults et al. (2013), (C) Hampton et al. (2007), (D) Hampton et al. (2010), (E) Manuszak et al. (2007), Hults et al. (2013), (F) Lowey (2018), and (G and H) Yokelson et al. (2015, and references therein). Details of the specific samples from Kalbas et al. (2007) and Hampton et al. (2007, 2010) that are included in the normalized age distribution diagrams (this study) are discussed in the text. Note that the y axis ranges from 0 to 540 Ma and Precambrian grains are not shown. Percentages of Precambrian grains for each group of samples, however, are shown in the far right of each row, under the location name and the number of detrital zircon analyses (n value) for each group of samples. Maximum depositional ages (MDA) and peak ages were generated from “Age Pick.” KA-AR = Kahiltna assemblage in the central Alaska Range; KA-SW = Kahiltna assemblage in the southwestern Alaska Range; KA-NW = Kahiltna assemblage in the northwestern Talkeetna Mountains; KA-CM = Kahiltna assemblage of the Clearwater Mountains in east-central Alaska; NMS = Nutzotin Mountains sequence in eastern Alaska; DF = Dezadeash formation in Yukon, Canada; WG = western strata of the Gravina belt in southeastern Alaska; EG = eastern strata of the Gravina belt in southeastern Alaska.

A third differentiating trend is the amount of Precambrian detrital zircons present. The basins containing Kahiltna assemblage in the central Alaska Range (Figure 12A), southwestern Alaska Range (Figure 12B), and the northwestern Talkeetna Mountains (Figure 12C) have a combined average of 18% Precambrian detrital zircon ages compared to a combined average of 2% for the other Jurassic-Cretaceous basins (Figures 12D–12H). These findings indicate a significant contribution of sediment from the Ancestral North American margin for the northern basins. We have discussed specific Precambrian sources for these grains earlier in the text.

Potential sediment links between along-strike basins include the Late Devonian-Mississippian detrital zircon age population with peak ages at 336 Ma in KA-SW, 346 Ma in KA-NW, 359 Ma in EG, and 362 Ma in KA-AR (Figures 12A–12C and 12H). This population indicates a link to Paleozoic sources of the Ancestral North American continental margin. The specific age ranges of these potential sources have been discussed earlier in the text. Other potential sediment links between these basins include the Silurian-Early Devonian detrital zircon age population with peak ages at 402 Ma in NMS, 420 Ma in EG, 429 Ma in WG, and 436 Ma in KA-AR (Figures 12A, 12E, 12G, and 12H). These ages best match with the plutonic ages in the outboard Alexander terrane (Figure 1). The late Early Cretaceous (Aptian to Albian) detrital zircon age population with peak ages at 119 Ma in KA-NW, 121 Ma in WG, and 123 Ma in KA-AR (Figures 12A, 12C, and 12G) are most likely sourced from plutons of the Chisana arc on the Wrangellia terrane (Figure 1) and provide another link to outboard sources of sediment. The Late Cretaceous detrital zircon age population with peak ages at 95 Ma in KA-SW and 98 Ma in KA-AR (Figures 12A and 12B) are confined to the Kahiltna assemblage in south-central Alaska. Late Cretaceous plutons and volcanic rocks intrude and overlie both the outboard and inboard terranes throughout the northern Cordillera (Armstrong, 1988; Gehrels et al., 2009; Moll-Stalcup, 1994; Plafker & Berg, 1994) and have been considered part of the post-collisional magmatic record. The absence of detrital zircon ages from the regionally extensive Late Cretaceous arc rocks in the Jurassic-Cretaceous basins in eastern Alaska (Figures 12D and 12E) and southeastern Alaska (Figures 12G and 12H) suggest that deposition may have ended earlier in these basins relative to the basins in south-central Alaska. As part of the Jurassic-Cretaceous basins, the Dezadeash Formation within the Dezadeash basin in Yukon, Canada also shows an absence of Late Cretaceous detrital zircon ages (Lowey, 2018). Lowey (2018) presents new U-Pb analyses of detrital zircons from the Dezadeash Formation that range from ~2111–145 Ma, with Mesozoic ages as the most abundant and a youngest dominant peak age at ~157 Ma (Figure 10A in Lowey, 2018). Figure 12 contains the recently published U-Pb detrital zircon data from the Dezadeash Formation (Figure 12F) and displays a similar detrital zircon age spectra to its interpreted offset equivalent, the Nutzotin Mountains sequence (Figure 12E) in eastern Alaska (e.g., Eisbacher, 1976; Lowey, 1998; Nokleberg et al., 1985).

Much more U-Pb detrital zircon geochronologic studies need to be conducted, especially with stratigraphic control and in combination with Lu-Hf isotopic analyses, from all of the Jurassic-Cretaceous along-strike basins to fully understand the tectonic significance of these basins. Our point in this discussion is that while these basins have traditionally been broadly grouped together because of their common Jurassic-Cretaceous biostratigraphic ages and their shared tectonic positions, by combining new tools such as detrital geochronology and Hf isotopes much more information can potentially be gleaned from these strata.

7. Conclusions

1. The Alaska Range suture zone is one part of a 2000-km-long crustal boundary that extends from southwestern Alaska to the state of Washington. In our study area, the suture zone juxtaposes metamorphic Paleoproterozoic-Triassic North American continental margin rocks, Paleozoic-Mesozoic oceanic rocks, and Jurassic-Cretaceous sedimentary strata within a Mesozoic collisional zone. U-Pb geochronology combined with Hf isotope geochemistry of detrital zircons document periods of major crustal melting and magmatic thickening correlative with global and regional Cordilleran tectonic events.
2. Results from our data record four Archean and Proterozoic crustal melting and magmatic thickening events that are correlated with the tectonic growth of western North America and Laurentia. In addition, three Phanerozoic crustal melting events identified in our integrated data sets are interpreted to represent more regional northwestern Cordilleran tectonic events.

3. A regional comparison of the U-Pb geochronology of detrital zircons from the Jurassic-Cretaceous sedimentary basin strata located along the 2000-km-long collisional boundary points out several differences and similarities. The Kahiltina basin, part of the Alaska Range suture zone, in south-central and southwestern Alaska have Triassic-Jurassic and Late Cretaceous detrital zircon populations that are distinct from the southern basins in southeastern Alaska, Yukon, and British Columbia. These southern basins are dominated by Jurassic detrital zircons; many of these zircons are interpreted to have been sourced from plutons intruded into the outboard oceanic terranes. The northern basins are interpreted to have a significant contribution of detritus from North American continental margin sources relative to the southern basins. The general absence of detrital zircons sourced from the regionally extensive Late Cretaceous arc rocks in the southern basins and their presence in the northern basins suggest that deposition may have ended earlier in the southern basins relative to the northern basins.
4. The approach of combining techniques such as U-Pb geochronology and Hf isotope geochemistry applied to detrital zircons has the potential to provide new insights into sediment provenance in collisional zones, as well as identify episodes of magmatism and crustal melting along convergent plate boundaries.

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