

Key Points:

- The Maclaren and Kluane schists were a single metamorphic belt that was offset by the Denali fault
- Prograde metamorphism of the Maclaren-Kluane schist took place along E-dipping structures in the late Cretaceous
- Offset of the Maclaren-Kluane schist and associated plutons record ~480 km of dextral displacement on the Denali fault since ca. 52 Ma

Supporting Information:

Supporting Information may be found in the online version of this article.

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Tectonic Underplating and Dismemberment of the Maclaren-Kluane Schist Records Late Cretaceous Terrane Accretion Polarity and ~480 km of Post-52 Ma Dextral Displacement on the Denali Fault

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Abstract Terrane accretion introduces irregular geometry and allochthonous material to obliquely convergent margins, which create opportunities to quantify strike-slip displacement along otherwise margin-parallel fault systems. We present new bedrock geologic mapping and U-Pb and ⁴⁰Ar/³⁹Ar geochronology from the Alaska Range suture zone in the eastern Alaska Range, which confirm a long-hypothesized correlation between the Maclaren Glacier metamorphic belt (Alaska, USA) and the Kluane metamorphic assemblage (Yukon Territory, Canada) across the right-lateral Denali fault. The new data inform a palinspastic reconstruction showing that the dissected metamorphic belts and associated plutons record ~480 km of dextral displacement along the Denali fault since ca. 52 Ma. Before strike-slip separation, the Maclaren-Kluane schist formed by west-vergent forearc underplating in the waning stage of the ca. 100–90 Ma arc built upon the Yukon-Tanana terrane. The prograde structural and metamorphic evolution of the Maclaren-Kluane schist records the final collision of the Wrangellia composite terrane at ca. 75–65 Ma along a set of east-dipping thrust shear zones, which we infer to record the polarity of the late Cretaceous plate boundary between the composite terrane and North America. Paleogene extension partially exhumed the schists to the upper crust and may be a consequence of regionally distributed strike-slip faulting at that time. Localization of the modern Denali fault after ca. 52 Ma dismembered the schists and four neighboring belts of plutonic, metasedimentary, and volcanic rocks. The transition to Yakutat oblique flat slab subduction at ca. 30–25 Ma marks the onset of transpressional deformation in the Denali fault system, which reactivated Late Cretaceous collisional structures bounding the Maclaren schist. Neogene reactivation of the Totschunda fault reduced strike-slip motion on the Denali fault east of the Denali-Totschunda intersection and continues to transfer residual plate boundary slip onto the Denali fault west of the intersection. Key outcomes of our synthesis include: (a) Much of the ~480 km of displacement on the Denali fault accumulated after strike-slip on the neighboring Tintina and Border Ranges fault systems had largely shut down; (b) The modern Denali fault system should not be grouped with strike-slip faults credited with large-scale margin-parallel transport of Cordilleran terranes in the Cretaceous. Instead, a poorly understood proto-Denali fault system may be a candidate for large-scale Cretaceous translation; and (c) the longevity (≥33 Myr) of the highly localized Denali fault master strand (≤1 km wide) implies that it occupies a major mechanical boundary that penetrates the lithosphere.

Plain Language Summary Many of the rocks that make up present-day western Canada and southern Alaska did not form as part of North America. Instead, most formed as coherent island chains (called terranes), collided with North America, and then slid northward along fault systems to their present location. The timing of collision and northward sliding of the terranes that make up western North America has been disputed for decades. To better bracket the timing of terrane collision and northward transport, we mapped and dated metamorphic and igneous rocks in southern Alaska that were sandwiched between western North America and the colliding terranes, then slid northward to Alaska via motion on the Denali fault. With the new maps and ages, we show that the terranes in southern Alaska collided with North America from about 90–65 million years ago, and then they moved northward along the Denali fault about 480 km (298 mi.) relative to correlative rocks in the Yukon Territory. Moreover, the youngest rocks that correlate across the Denali fault are about 52 million years old, which allows us to bracket the timing of the ~480 km of motion on the Denali fault to have happened since 52 million years ago. Before our study, the Denali fault was thought to have moved ~370–400 km (230–250 mi.) since about

100 million years ago. Our improved estimates of timing and magnitude of motion on the Denali fault better bracket the former locations of rocks that make up western North America, which informs general questions about how continents grow, how fault systems evolve, and what geological processes lead to uplifted topography along continental margins.

1. Introduction

Quantitative restoration of strike-slip deformation along obliquely convergent margins is commonly hindered by strike-slip localization within the arc (e.g., Busby-Spera & Saleeby, 1990; Lange et al., 2008) or forearc (Avé Lallemant, 1997; Jarrard, 1986), which translates sub-parallel elements of the margin relative to each other but may not cross-cut restorable features (Beck, 1986). Terrane accretion and associated geometric modification of the margin (e.g., Dominguez et al., 1998) form unique markers that may be used to track syn-collisional and post-collisional margin-parallel translation. Recognition, correlation, and restoration of such features requires identifying the suite of diagnostic characteristics by which they can be identified, knowledge of where/when the feature accreted to the margin, and how each part of the displaced feature has evolved since dismemberment.

Assembly of the North American Cordillera involved multiple episodes of strike-slip faulting and terrane accretion. Although both terrane accretion and translation have long been recognized as fundamental geologic processes shaping western North America (e.g., Coney et al., 1980; Moores, 1970), they persist as controversial topics. Shortening structures formed during terrane accretion are essential for reconstructing strike-slip deformation in the Cordillera because they have been found in multiple places to be cut by strike-slip faults and thus create reliable geological markers for estimating strike-slip separation (Gabrielse et al., 2006; Nokleberg et al., 1985). New views of the Mesozoic Cordilleran orogeny (Hildebrand, 2015; Johnston, 2008; Sigloch & Mihalynuk, 2017), however, call into question the timing and polarity of various terrane accretionary events (e.g., Pavlis et al., 2019). A detailed reappraisal of terrane accretionary rocks and structures is thus necessary to vet the various models of Cordilleran assembly and associated margin-parallel translation.

Metamorphic belts and structures formed during the closure of the ocean basin between the Wrangellia composite terrane and North America have been used to estimate total strike-slip displacement on the Denali fault between southern Alaska, USA and southwestern Yukon Territory, Canada. The purported correlative rock packages include schists, gneisses, and plutons in the Maclaren Glacier metamorphic belt¹ (Alaska) and Kluane metamorphic assemblage-Ruby Range batholith (Yukon) (Eisbacher, 1976; Nokleberg et al., 1985; Figure 1). Since the correlation between these two metamorphic belts was first proposed by Forbes et al. (1974), the tectono-metamorphic evolution of the Kluane metamorphic assemblage has been the focus of a number of detailed studies (e.g., Canil et al., 2015; Israel et al., 2011; Mezger, 1999, 2002; Mezger, Chacko, et al., 2001; Mezger, Creaser, et al., 2001; Stanley, 2012). In contrast, metamorphic and plutonic rocks near the Maclaren Glacier have mainly been studied as part of early regional mapping efforts (Nokleberg et al., 1985; Nokleberg, Aleinikoff, Lange, et al., 1992; Smith, 1981), other than detailed studies in a small accessible region (Beam & Fisher, 1999; Davidson & McPhillips, 2007; Davidson et al., 1992; Link, 2017). The difference in study resolution has led to doubt as to whether the rock units correlate (e.g., Mezger, Chacko, et al., 2001). Moreover, tectonic models describing the prograde metamorphic path of the Maclaren and Kluane belts have argued for opposing vergence directions for syn-collisional structures (cf., Csejtey et al., 1982; Erdmer & Mortensen, 1993; Johnston & Canil, 2007; Nokleberg et al., 1985). If the disparate tectonic models are correct, then the proposed correlation of the Maclaren and Kluane belts may be refutable and estimates of total displacement along the Denali fault system would require revision.

Here, we present a new regional synthesis map (Figure 2), zircon U-Pb age data from 9 metasedimentary and 13 plutonic samples, zircon Hf isotopic data from three metasedimentary samples, and ⁴⁰Ar/³⁹Ar geochronology on four volcanic samples located south of the Denali fault in the eastern Alaska Range. Our data bear on the timing of initial burial and tectono-metamorphic evolution of the Maclaren and Clearwater metasedimentary belts in Alaska leading up to and after strike-slip separation. We compare our data to equivalent data sets from the Kluane metamorphic assemblage and argue that the metasedimentary/plutonic belts represent a single body that was cut and displaced by the Denali fault. By integrating our data

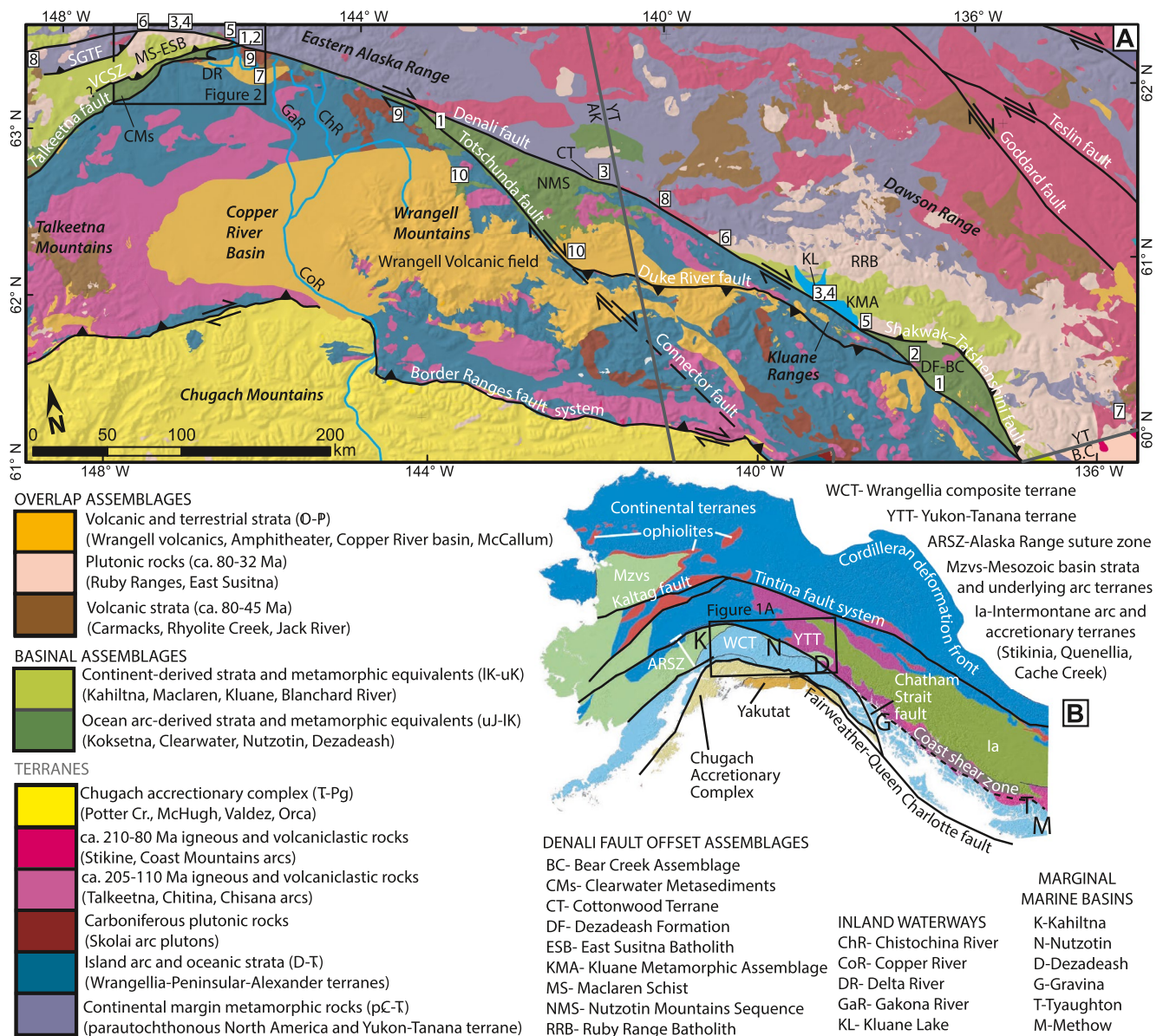


Figure 1. (a) Simplified geologic map of the southwestern Yukon and eastern Alaska region surrounding the Denali fault (modified from Wilson et al. [2015] and Colpron et al. [2016]). Basement geology is combined into the Wrangellia and Yukon composite terranes south and north of the Denali fault, respectively. Mesozoic-Cenozoic igneous belts and basinal assemblages are delineated as either pre-Wrangellia-collisional terranes and marginal marine strata (≥ 80 Ma) or overlap (< 80 Ma). The legend contains regional formation, metamorphic belt, or plutonic suite names that are contained within the map area and are pertinent to the study. The location of Figure 2 is contained within the black box. Boxed numbers denote the locations of correlative geologic features that are listed in Table 1. SGTF—Susitna Glacier thrust fault; VCSZ—Valdez Creek shear zone; AK—Alaska; YT—Yukon Territory; B.C.—British Columbia. (b) Regional terrane map of the Canadian-Alaska Cordillera showing the location of Figure 1A and major strike-slip fault systems (black lines), modified from Colpron and Nelson (2011). Abbreviations denoting the marginal marine basins are shown in the general locations.

with other regional data sets, we are able to place the Maclaren-Kluane metamorphic belt into a regional tectonic framework during the final accretion of the Wrangellia composite terrane and arrive at more precise measurements and timing of subsequent strike-slip separation.

¹Recent studies by Link (2017) and Waldien et al. (2021) have shown that the Maclaren Glacier metamorphic belt is a composite metamorphic belt wherein rocks at various structural positions have different prograde metamorphic histories, which experienced different metamorphic, magmatic, and structural histories before final juxtaposition by the Valdez Creek shear zone during Wrangellia composite terrane accretion to North America. The

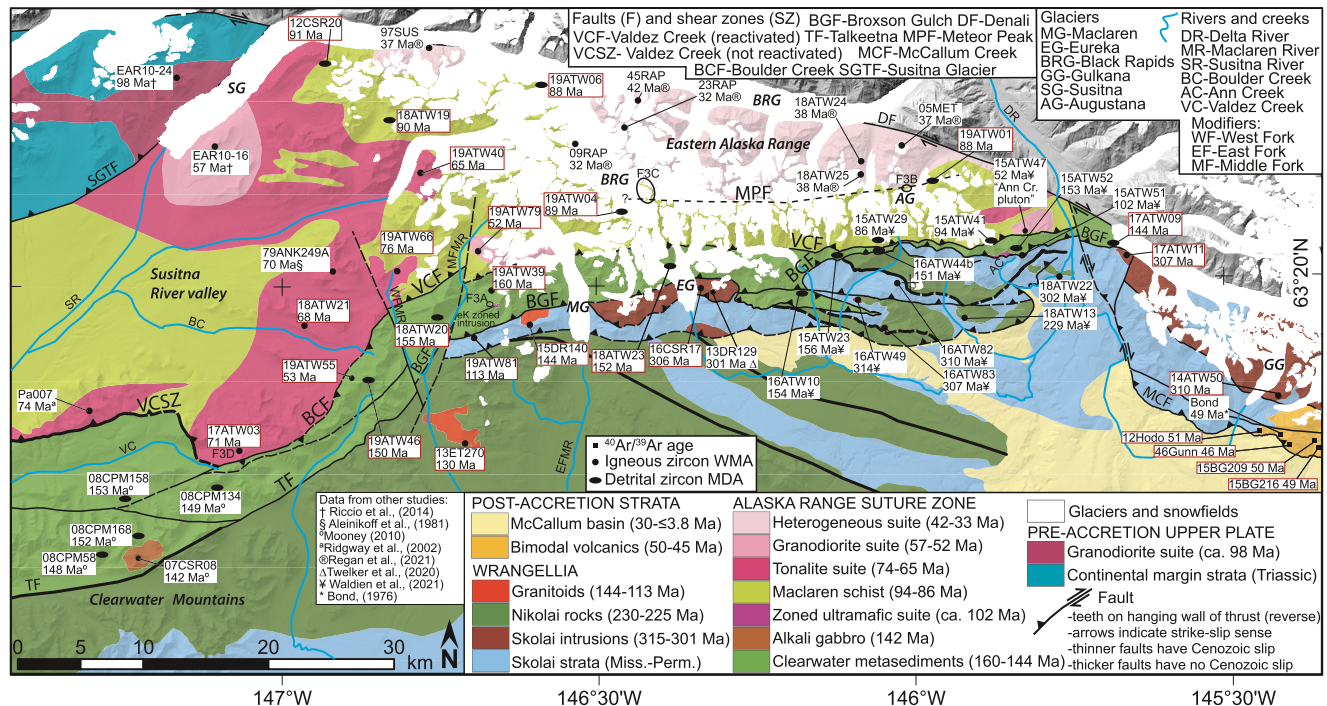


Figure 2. Regional geologic and age compilation map of the study area in the eastern Alaska Range. The map is compiled from Smith and Turner (1974), Mooney (2010), Waldien et al. (2018), Twelker et al. (2020), Waldien et al. (2021), and our new mapping near the headwaters of the Maclaren River. Previously published ages are annotated with a symbol corresponding to an author, whereas new ages are outlined by a red box. The locations of field photographs in Figure 3 are shown as “F3A-D.” WMA—weighted mean age; MDA—maximum depositional age.

term “Maclaren Glacier metamorphic belt” as originally defined does not convey the disparate polyphase tectonic evolution of the metamorphic rocks in the area. We propose that the recent advances in understanding have rendered the term “Maclaren Glacier metamorphic belt” obsolete. We argue that parsing the metamorphic rocks into the Maclaren schist/gneiss (structurally above the Valdez Creek shear zone) and Clearwater metasediments (structurally below the Valdez Creek shear zone) is more informative and thus will be more useful for future studies in the region.

2. Geologic Background

2.1. Slip on the Modern Denali Fault

The Denali fault system is an arcuate set of structures that transect the Cordillera from northern British Columbia to western Alaska (St. Amand, 1957). Active dextral slip is likely routed to the Denali fault master strand from the plate boundary fault systems by way of the Connector fault (Brothers et al., 2018; Choi et al., 2021; Doser, 2014; Elliott & Freymueller, 2020; Figure 1). Published estimates of total offset on the Denali fault range from 370 to 400 km and are based on a variety of offset markers ranging from topography to terrane boundaries. Lowey (1998) provided a synopsis of strike-slip displacement estimates and Table 1 contains an updated list of separation estimates for the Denali fault, including those presented here for the first time. It is important to emphasize that the tabulated separation estimates consider only the active strand of the Denali fault. We recognize the likelihood of an older Denali fault system, which may have had multiple strands active during the Cretaceous (McDermott et al., 2019; Miller et al., 2002; Wahrhaftig et al., 1975). Herein, our use of the words *Denali fault* refers to the active strand of the fault, which appears to have been a single highly localized strand for much of the Cenozoic (Cole et al., 1999; Regan et al., 2021). When necessary for clarity, we distinguish the *modern-* or *proto-* Denali fault to refer to the Cenozoic and Cretaceous fault systems, respectively. Our use of the words *Denali fault system* includes the active Denali fault master strand, Totschunda fault, and thrust systems at the northern and southern flanks of the Alaska Range.

Table 1
Offset Markers for the Modern Denali Fault System

Reference	Fault section	Offset markers	Separation and Timing	Number on Figure 1
Lowey (1998)	Eastern Denali	Dissected megaboulder channel in Dezadeash (YT)-Nutzotin (AK) strata	370 km since 52 Ma ^b	1
Waldien et al. (2021)	Eastern Denali	Clearwater metasediments (AK)-Dezadeash formation (YT)	465 km since 52 Ma ^b	1
Waldien et al. (2021)	Eastern Denali	Granodiorite and pyroxenite near Ann Creek (AK)-Shorty Creek granodiorite and Pyroxenite Cr. Pyroxenite (YT) ^a	≤505 km since 52 Ma ^b	2
Regan et al. (2021), This study	Eastern Denali	Cottonwoods schist (AK)-Maclaren schist (AK)	305 km since 33 Ma	3
		Cottonwood schist (AK)-Kluane schist (YT)	100–125 km, 52–33 Ma	
Nokleberg et al. (1985), Riccio et al. (2014)	Eastern Denali	Maclaren schist and East Susitna batholith (AK)-Kluane schist and Ruby Range batholith (YT)	445 km since 52 Ma ^b	4
This Study	Eastern Denali	ca. 52 Ma Shakwak pluton (YT)-Ann Creek pluton (AK)	465 km since 52 Ma	5
		74–65 Ma intrusions within Kluane schist and Maclaren schist ^a	≥425 km since 52 Ma	6
		Eocene bimodal volcanic strata near Gakona Gl. (AK)-Bennett Lake igneous complex (YT) ^a	≤580 km since 52 Ma ^a	7
		Jack River igneous field (AK)-Rhyolite Creek volcanics (YT) ^a	≤490 km since 52 Ma ^b	8
This Study; D. Murphy personal communication	Eastern Denali	Kluhini River Thrust (YT)-Susitna Glacier thrust (AK)	≥425 km post 52 Ma ^b	7
Waldien et al. (2018)	Totschunda-Eastern Denali	Strain compatibility with fault linkage	≤91 km since 7 Ma	9
Berkelhammer et al. (2019)	Totschunda	Wrangell volcanics and intrusions (AK)	≤85 km since 7 Ma ^b	10
Fasulo et al. (2020); This study	Totschunda-Eastern Denali	Nutzotin basin strata and associated ca. 120 Ma intrusions (AK)	>75 km since 7 Ma ^b	Similar to 9
Allen et al. (2016)	Totschunda-Eastern Denali	Transtensional lower McCallum basin (AK) to transtension zone at Denali-Totschunda intersection (AK)	<95 km since 7 Ma ^b	Similar to 9
Regan et al. (2021)	Central Denali	Schist Creek pluton-Foraker pluton (AK)	155 km since 37 Ma	Not Shown
Trop et al. (2019)	Central Denali	Colorado Cr. basin detritus-eastern Alaska Range sources (AK)	150 km since 29 Ma	Not Shown
Miller et al. (2002)	Western Denali	Algal Reef in Farewell terrane strata (AK)	134 km, post mid-K	Not Shown

^aCorrelated features may be different bodies. ^bSeparation re-measured and/or new timing inferred from our data.

2.2. Mesozoic Terrane Accretion and Strike-Slip Faulting in the Cordillera

The Mesozoic geologic evolution of the North American Cordillera is characterized by accretion and margin-parallel transport of allochthonous terranes (Colpron et al., 2015; Coney et al., 1980; Nelson & Colpron, 2007). The outboard belt of the Cordillera is largely composed of Paleozoic and Mesozoic arc rocks belonging to the Wrangellia, Peninsular, and Alexander terranes, which had accreted to each other before collision with the Cordilleran margin (Beranek et al., 2014; Gardner et al., 1988; Israel et al., 2014). Herein, we refer to the amalgamated terranes as the “Wrangellia composite terrane” and distinguish the individual terranes only when necessary. The structural polarity during accretion of the Wrangellia composite terrane to the Cordillera is disputed; some authors argue for west-dipping subduction (Hildebrand, 2015; Lowey, 2019; Sigloch & Mihalynuk, 2017), whereas others argue for east-dipping collisional structures and an unclear role of subduction during the collision (Pavlis et al., 2019; Trop & Ridgway, 2007). Regardless of structural polarity, the collision coincided with along-strike diachronous oblique closure of a marginal marine basin system from Late Jurassic to Late Cretaceous (Manselle et al., 2020; McClelland et al., 1992; Ridgway et al., 2002). Deformed and variably metamorphosed packages of clastic strata representing the

closed marginal marine basins are exposed over 3,000 km length of the Cordillera from southern British Columbia to western Alaska (Methow-Tyughton-Gravina-Dezadeash-Nutzotin-Kahiltina basins—Figure 1b). In southern Alaska, the highly deformed region underlain by imbricated and metamorphosed Kahiltina basin strata, fragments of oceanic crust, and disparate continental terranes is referred to as the Alaska Range suture zone (Fitzgerald et al., 2014; Ridgway et al., 2002; Trop et al., 2019; ARSZ—Figure 1b).

Syn-collisional and post-collisional strike-slip faulting contributed to margin-parallel transport of the Wrangellia composite terrane and dismemberment of the basal assemblages along the inboard margin of the composite terrane. The strike-slip faulting is generally taken to accommodate the margin-parallel component of oblique relative plate motion between western North America and outboard oceanic plates (e.g., Monger & Gibson, 2019). Regional deformation patterns are consistent with southward transport of outboard terranes along sinistral fault systems during the Late Jurassic and Early Cretaceous (Chardon et al., 1999; Cobbett et al., 2017; Evenchick, 1991; Israel et al., 2006; Mahoney et al., 2009; Monger et al., 1994). By the Late Cretaceous, widespread dextral shear in the Cordillera contributed to northward transport of the terranes relative to the North American craton, which continued into the Cenozoic (Avé Lallemant & Oldow, 1988; Wyld et al., 2006). Many paleomagnetic-based studies call for large-scale (>1,500 km) of Cretaceous-Cenozoic northward displacement of the Cordilleran terranes (e.g., Enkin, 2006; Hillhouse & Coe, 1994; Johnston, Jane Wynne, et al., 1996; Stamatakis et al., 2001). However, the sum of geology-based slip estimates does not reach the magnitude of translation inferred from the paleomagnetic estimates (e.g., Wyld et al., 2006), thus implying the potential for missing slip.

Much of the strike length of the Denali fault marks the boundary between rocks belonging to, or derived from, the Wrangellia composite terrane and rocks with peri-continental affinity. Thermochronological, structural, and stratigraphic data sets suggest that oblique closure of the Kahiltina basin, and associated development of the Alaska Range suture zone, involved slip on a potentially multi-stranded proto-Denali fault system along the paleo-eastern margin of the Wrangellia composite terrane, which may have translated the composite terrane relative to Mesozoic strata to the east (McDermott et al., 2019; Trop et al., 2020). In contrast, the modern Denali fault cuts obliquely through the Mesozoic basal assemblages, continental margin rocks, and plutonic belts (Figure 1). The section of the Denali fault between the longitudes of the Delta River (~145.5°W—Alaska) and Kluane Lake (~139°W—Yukon) juxtaposes the Wrangellia terrane rocks directly against peri-Laurentian rocks, whereas Mesozoic basin strata and associated crystalline rocks are largely absent from that section of the fault system (Figure 1a). The similarities among Mesozoic-Paleogene rocks near the Delta River and Kluane Lake, and lack of similar rocks between the two areas, has made them a target for estimating offset on the modern Denali fault (e.g., Eisbacher, 1976; Nokleberg et al., 1985).

2.3. Geology South of the Denali Fault Near the Delta River in the Eastern Alaska Range

South of the Denali fault and west of the Delta River, a series of north-dipping thrust panels contain Triassic continental margin strata, Alaska Range suture zone metasedimentary and plutonic rocks, and Wrangellia terrane meta-igneous rocks. From north to south, important structures bounding the thrust panels are the Susitna Glacier thrust fault, Valdez Creek shear zone/fault, and the Talkeetna-Broxson Gulch fault (Figures 1a and 2).

The Triassic continental margin rocks in the northernmost and structurally highest panel south of the Denali fault comprise carbonate and clastic strata that are intruded by ca. 98–57 Ma plutons in the hanging wall of the Susitna Glacier thrust fault (Csejtey et al., 1992; Riccio et al., 2014). In the footwall south of the Susitna Glacier thrust fault, amphibolite facies pelitic-to-quartzofeldspathic schists and gneisses of the Maclaren schist are intruded by the East Susitna batholith (Davidson et al., 1992; Nokleberg et al., 1985; Waldien et al., 2021). Individual plutons within the East Susitna batholith have yielded crystallization ages ranging from ca. 74–33 Ma (Aleinikoff et al., 1981; Davidson & McPhillips, 2007; Regan et al., 2021; Ridgway et al., 2002; Turner & Smith, 1974). Across the Valdez Creek fault/shear zone to the south, the Clearwater metasediments comprise ca. 160–144 Ma generally arkosic-to-mafic metasedimentary strata with lesser argillaceous slate and phyllite, which are intruded by small volume intermediate-to-ultramafic intrusions with crystallization ages ranging from ca. 142–102 Ma (Mooney, 2010; Waldien et al., 2021). The Talkeetna-Broxson Gulch fault juxtaposes the metasedimentary and plutonic rocks in the north against the Wrangellia terrane to the south.

In the eastern Alaska Range, Wrangellia stratigraphy consists of Carboniferous volcanic and volcanoclastic strata overlain by lesser Permian carbonate strata and regionally extensive Triassic flood basalts. The Carboniferous strata in the area host generally intermediate composition intrusions dated at ca. 300–315 Ma (Waldien et al., 2021). Both the strata and the intrusions have been linked to the Skolai arc that forms the nucleus of the Wrangellia terrane in south-central Alaska (Bond, 1973; Beard and Barker, 1989). Carbonate strata containing Early Permian fossils unconformably overly the Skolai arc rocks (Bond, 1973, 1976; Nokleberg, Aleinikoff, Dutro, et al., 1992; Richter & Dutro, 1975) and may record cessation of Skolai arc magmatism in the Late Pennsylvanian (e.g., Beranek et al., 2014; Israel et al., 2014). Triassic Nikolai flood basalt strata unconformably overly the Paleozoic rocks in the region (Greene et al., 2008; 2010; Twelker et al., 2020). Nikolai strata and associated intrusions yield crystallization ages of 225–230 Ma (Bittenbender et al., 2007; Greene et al., 2010; Twelker et al., 2020; Waldien et al., 2021).

South of the Denali fault and east of the Delta River, a belt of Eocene felsic volcanic rocks with lesser basalt unconformably overlies and is faulted against pre-Cenozoic Wrangellia rocks between the Delta River in the west and the Chistochina River in the east (Nokleberg, Aleinikoff, Lange, et al., 1992; Gillis et al., 2019; Figures 1 and 2). The Eocene volcanic strata and Wrangellia rocks are carried in the hanging wall of the south-vergent McCallum-Slate Creek thrust system. The footwall south of the McCallum-Slate Creek thrust system contains the Oligocene-Pliocene fluvial-lacustrine McCallum basin strata (Allen et al., 2016; Waldien et al., 2018).

The tectono-metamorphic evolution of rocks south of the Denali fault near the Delta River records imbrication of North American-affinity and Wrangellia-affinity rocks during Late Cretaceous terrane accretion and Oligocene reactivation of the terrane accretionary structures. Before juxtaposition during terrane accretion, the Maclaren schist protolith was derived from, and deposited upon, the western margin of North America at ca. 94–86 Ma, whereas the Clearwater metasediments were deposited along the paleo-eastern margin of the Wrangellia terrane at ca. 150 Ma (Waldien et al., 2021). Initial juxtaposition of the Maclaren schist and Clearwater metasediments took place with the formation of the Valdez Creek shear zone, which is a south-vergent thrust shear zone intruded by a ca. 74 Ma syn-kinematic tonalite sill (Ridgway et al., 2002). Motion on the shear zone produced a well-preserved inverted metamorphic gradient in the footwall Clearwater metasediments, which records the Late Cretaceous history of prograde metamorphism related to Wrangellia terrane accretion (Davidson et al., 1992; Hollister, 1993; Smith, 1981). In the Alaska Range east of the Maclaren River, the Maclaren schist experienced a pervasive greenschist facies retrograde metamorphic overprint that has been linked to post-32 Ma reactivation of the Valdez Creek shear zone as the Valdez Creek fault (Waldien et al., 2021). Reactivation of the shear zone nucleated a south-vergent imbricate thrust system that includes the Broxson Gulch fault at the northern margin of the Wrangellia terrane and reverse faults within the Wrangellia terrane to the south (Waldien et al., 2021). The Denali fault truncates the Maclaren schist and associated rocks and structures near the Delta River (Figures 1 and 2).

2.4. Geology Northeast of the Denali Fault Near Kluane Lake in Southwestern Yukon

Near Kluane Lake northeast of the Denali fault, a series of north-to-northeast-dipping thrust panels contain peri-Laurentian Yukon-Tanana terrane rocks, the Kluane Metamorphic assemblage, the Dezadeash Formation, and the Bear Creek Formation. Important structures in the region are the Kluhini River thrust and the Tatshenshini shear zone/Shakwak fault.

Rocks belonging to the Yukon-Tanana terrane occupy the highest structural panel, which consists of pre-Carboniferous quartzose metasedimentary rocks with lesser carbonate and amphibolite that host late Devonian and younger intrusions (Israel et al., 2011; Johnston, Mortensens, et al., 1996). South of the Yukon-Tanana terrane, the Ruby Range batholith is a ca. 77–57 Ma composite intrusive suite emplaced along the boundary between Yukon-Tanana terrane rocks to the north and the Kluane metamorphic assemblage to the south (Israel et al., 2011; Stanley, 2012). The Kluane metamorphic assemblage consists of Late Cretaceous amphibolite facies pelitic and quartzofeldspathic schist and gneiss (Mezger, Chacko, et al., 2001). For simplicity, we hereafter refer to these metasedimentary rocks as the Kluane schist. The batholith largely obscures the contact between the Kluane schist and Yukon Tanana terrane, yet vestiges of a Late Cretaceous west-vergent thrust shear zone (Kluhini River thrust-Vice et al., 2020) are preserved. Smaller intrusions within the 54–48 Ma Hayden Lake suite intruded the lowest structural position of the Kluane schist

(Colpron et al., 2016). Graben-bounded Paleogene volcanic strata unconformably overlie Yukon-Tanana terrane metamorphic assemblages and associated plutons throughout southwestern Yukon.

The southern margin of the Ruby Range batholith and Kluane schist are juxtaposed against Dezadeash and Bear Creek strata to the southwest along the Shakwak fault and Tatshenshini shear zone (Colpron et al., 2016; Lowey, 2000; Vice et al., 2020). The Bear Creek assemblage consists of Upper Triassic marine strata and lava flows (Israel et al., 2015). The Late Jurassic-Early Cretaceous Dezadeash Formation unconformably overlies the Bear Creek assemblage and consists of ≥ 1 km of marine turbidite strata (Eisbacher, 1976; Lowey, 1998). Both the Bear Creek and Dezadeash strata host the ca. 126–106 Ma (K-Ar dates) Shorty Creek and Pyroxenite Creek intermediate-ultramafic intrusive suite (Dodds & Campbell, 1988; Eisbacher, 1976). The northwest-striking Denali fault truncates the western margin of the entire package of north-dipping structural panels in southwestern Yukon.

The geologic evolution of rocks near Kluane Lake records the closure of an ocean basin during the Late Cretaceous (Mezger, Creaser, et al., 2001). Detrital zircon U-Pb data indicate that both schistose and gneissic Kluane rocks have ca. 95–90 Ma protolith ages and received sediment from Yukon-Tanana and other peri-Laurentian terranes (Israel et al., 2011; Stanley, 2012) before imbrication and prograde metamorphism along east-northeast-dipping convergent structures (Erdmer & Mortensen, 1993). In contrast, the Dezadeash Formation was likely sourced from the Mesozoic arcs built upon the Wrangellia composite terrane as indicated by paleo-current indicators and detrital zircon U-Pb age spectra (Lowey, 2019). Similarly, the Bear Creek Formation may correlate with similar age and composition rocks within the Alexander terrane (Israel et al., 2015). During Wrangellia composite terrane accretion, the Kluane schist experienced regional metamorphism as early as 82 Ma and was intruded by the Ruby Range batholith from ca. 77 to 57 Ma (Israel et al., 2011; Stanley, 2012). The ca. 57 Ma phase of the Ruby Range batholith displays regional plutonic-to-volcanic textural gradation that links it to the Rhyolite Creek volcanics to the north (Israel et al., 2011), which may record tilting of the crustal section following terrane accretion (Johnston & Canil, 2007).

3. Methods

3.1. Geologic Mapping

We performed 1:20,000-scale bedrock geologic mapping during the summers of 2018 and 2019 on base maps constructed from IFSAR Alaska and ArcticDEM digital terrain models. Mapping focused on along-strike correlation of major structures and bedrock units between the eastern Alaska Range and Clearwater mountains. Here, we present a new bedrock geologic map (Figure 2), compiled from the new mapping and prior mapping by Turner and Smith (1974), Smith (1981), Mooney (2010), Waldien et al. (2018), Twelker et al. (2020), and Waldien et al. (2021).

3.2. Separation Measurements

We measured the strike-slip separation of correlative rock units along the Denali fault on a NAD83 Alaska Albers Conic equal area projection using the *ruler* tool in ESRI Arcmap. If the body of rock used for measurement is cut by the Denali fault, then measurements represent the distance between the midpoints of the cut faces of the correlative bodies. If the body is not mapped as cut by the Denali fault, then we measured from the location on the fault nearest to the body. Differences in deformation, rotation, and erosional exhumation of the correlative rocks on opposite sides of the fault introduce uncertainty into the separation measurements that are difficult to quantify. A simple trigonometric calculation accounting for the dip of reactivated structures near the Delta River (~ 40 – 70° N), the inferred differential exhumation between the Maclaren and Kluane schist (~ 5 – 10 km), and the timing of the differential exhumation relative to slip on the Denali fault (post-32 Ma exhumation of Maclaren schist; Waldien et al., 2021) suggests that separation measurements have associated uncertainties as great as ~ 8.5 km. Instead of measurement-specific uncertainties, we infer that the measurements of strike-slip separation presented and discussed herein have associated uncertainties of less than ± 10 km.

3.3. Zircon U-Pb Dating

3.3.1. Sample Preparation and Data Collection

We performed single-grain zircon U-Pb geochronology by Laser Ablation Quadrupole Inductively Couple Mass Spectrometry (LA-Q-ICP-MS) with three primary goals: (a) to fingerprint metasedimentary rocks by determining the sediment source areas of the protolith, (b) to estimate the maximum depositional age of the protolith, and (c) to date igneous intrusions in the map area. Mineral separation at UC Davis involved standard crushing techniques, a miner's gold pan, Frantz isodynamic separator, and Lithium Polytungstate and/or Methylene Iodide heavy liquids to concentrate zircon grains. For detrital zircon samples, we concentrated zircon grains enough to mount them by pouring; for igneous samples we hand-picked relatively large, inclusion-sparse zircon grains. Before LA-Q-ICP-MS analysis, we mounted the zircon grains and reference materials into 1 in. epoxy rounds, polished the rounds to expose the grain surface, and imaged them using a Cameca SX-100 Electron Microprobe. High-contrast back-scattered electron images allowed us to identify zoning and/or inherited cores in individual zircon grains, which informed our laser spot placement on each grain. We collected isotopic data using an Agilent 7700 series Q-ICP-MS coupled to a Photon Machines 193 nm Excimer laser ablation system at UC Davis. By polishing the grain mounts until zircon surfaces are exposed, rather than grinding to the core of the crystal, we were in some cases able to ablate through metamorphic rims into detrital cores. We obtained dates on both the rim and core using the *VizualAge* plug-in as implemented with the *U_Pb_geochronology3* data reduction scheme in the *Iolite* program (Paton et al., 2010; Petrus & Kamber, 2012). Supporting Information S1 contains detailed mineral extraction, analytical, data reduction, and data filtering methods used in the LA-Q-ICP-MS analyses. Supporting Information S2 contains the single-grain U-Pb data.

3.3.2. Data Presentation

Our fingerprinting of metasedimentary protoliths is based on identifying distinctive populations of detrital zircon single-grain U-Pb dates. Each multimodal detrital zircon age data set contains analyses on at least 117 grains (Vermeesch, 2004). One detrital sample displays a unimodal age spectrum that is defined by 50 single-grain analyses. We represent the detrital U-Pb data as Kernel Density Estimates using the *DZStats* and *Density Plotter* programs (Saylor & Sundell, 2016; Vermeesch, 2012, respectively). Because many of the rocks analyzed in our study experienced amphibolite and upper greenschist metamorphic temperatures and thus may have experienced metamorphic recrystallization and/or lead loss (e.g., Hoskin & Schaltegger, 2003), we screened each analysis from the youngest age population of each sample to parse detrital and post-depositional metamorphic grains based on U content (ppm), U/Th ratio, imaged zoning patterns, age relative to the known ages of intrusions within the rock unit, and presence of age zoning revealed by laser depth profiling (Supporting Information S1). After parsing detrital and metamorphic grains, we calculated a maximum depositional age for each sample using the age of the youngest statistical population of the detrital grains (e.g., Herriott et al., 2019).

We used *Isoplot* (Ludwig, 2008) to determine the ages of igneous zircon populations by calculating the weighted mean of single grain dates with internal 2 s errors. Reported uncertainties of weighted mean ages represent 95% confidence interval internal uncertainties and the quadratic addition of external uncertainties (e.g., Horstwood et al., 2016; Supporting Information S1).

3.3.3. Statistical Tests

To assess the similarities between metasedimentary assemblages across the Denali fault, we performed statistical tests on the detrital zircon U-Pb age data using the multidimensional scaling program *DZmDS* from Saylor et al. (2018). We focused our multidimensional scaling approach on the cross-correlation of probability density distributions because that approach has been shown to work well with both simple and complex data sets that range in sample size (Saylor & Sundell, 2016).

3.4. Hf Isotopic Data

To refine sediment source areas of metasedimentary protoliths, we performed Hf isotopic analysis on Mesozoic detrital zircon grains from two samples of Clearwater metasediment and one sample of Maclaren schist. Hf analyses employed a Photon Machines 193 nm Analyte G2 excimer laser (40 μ m spot size)

coupled to a Nu High-Resolution Multicollector ICP-MS at the Arizona Laserchron Center. The analytical approach used the sample bracketing technique, wherein we performed at least one analysis on each of the six reference materials (FC, Mud Tank, 91500, Temora, Plesovice, R-33, and Sri Lanka natural zircon) between every 15–20 unknowns. U-Pb age data for the analyzed grains are published in Waldien et al. (2021). Complete Hf analysis methods and data are available in Supporting Information S1.

3.5. $^{40}\text{Ar}/^{39}\text{Ar}$ Dating Methods

To determine the age of faulted volcanic rocks, we conducted $^{40}\text{Ar}/^{39}\text{Ar}$ analyses at the Geochronology Laboratory at the University of Alaska, Fairbanks, where we crushed, sieved, washed, and hand-picked samples to obtain a pure phase of phenocryst-free groundmass or biotite. The sample aliquots and monitor mineral MMhb-1 (Samson & Alexander, 1987), which has an age of 523.5 Ma (Renne et al., 1994), were irradiated at McMaster University in Hamilton, Ontario, Canada. Upon their return from the reactor, we loaded the samples and monitors into 2 mm diameter holes in a copper tray and then loaded them into an ultra-high vacuum extraction line. The monitors were fused, and samples heated, using a 6-W argon-ion laser following the technique described in York et al. (1981), Layer et al. (1987), and Benowitz et al. (2014). Ar isotope measurements in this system are made using a VG-3600 mass spectrometer.

Supporting Information S3 contains detailed $^{40}\text{Ar}/^{39}\text{Ar}$ analytical methods and contains the $^{40}\text{Ar}/^{39}\text{Ar}$ data, wherein all ages are reported at the 1σ level and calculated using the constants of Renne et al. (2010). The integrated age is the age given by the total gas measured and is equivalent to a potassium-argon (K-Ar) age. The spectrum provides a plateau age if three or more consecutive gas fractions represent at least 50% of the total gas release and are within two standard deviations of each other (mean square weighted deviation <2.5).

4. Results

4.1. New Mapping and Synthesis With Existing Maps

Our new mapping and U-Pb geochronology (discussed below) link the two regions of previously detailed mapping to the west (Smith, 1981) and east (Waldien et al., 2021). Accordingly, the mapping presented herein addresses the correlation between Mesozoic structures in the Clearwater Mountains (bold faults on Figure 2) and reactivated versions of those structures to the east (thin faults on Figure 2). The transition between reactivated and non-reactivated structures broadly coincides with the Maclaren River, which is also the location of a 1:250,000-scale quadrangle boundary (147°W) (cf., Csejtey et al., 1992; Nokleberg, Aleinikoff, Lange, et al., 1992; Wilson et al., 1998, 2015). To our knowledge, our study is the first to attempt to correlate the geology across the region. Our along-strike correlation of structures from the Clearwater Mountains to the eastern Alaska Range relies on the continuity of distinct rock packages between the two regions (Figure 2).

4.1.1. Geology of the Maclaren River Corridor

The 10-km-wide region between the Maclaren Glacier in the east and west fork of the Maclaren River in the west exposes the Maclaren schist, Clearwater metasediments, and the Wrangellia terrane (Figure 2). The structurally highest panel contains the Maclaren schist and a cross-cutting granodiorite body carried in the hanging wall of the Valdez Creek fault. South of the Valdez Creek fault, the Clearwater metasediments in this region are dominated by fine-grained metagreywacke and slate. East of the middle fork of the Maclaren River, the metasediments host a volumetrically small zoned gabbro-diorite intrusion. Diorite dikes near the intrusion are folded with the foliation in the Clearwater slate (Figure 3a). Due to the composition of the intrusion, the zonal structure, and the deformation shared with the host rocks, we infer that the intrusion is Early Cretaceous in age, which has been documented within the Clearwater metasediments to both the east and southwest (Mooney, 2010; Waldien et al., 2021). The Clearwater metasediments and associated intrusions were thrust southward over Wrangellia terrane rocks, which in this region are predominantly composed of Nikolai rocks and lesser Permian carbonate strata in the north near the Broxson Gulch fault. The Wrangellia strata host zoned intermediate-mafic composition granitoids.

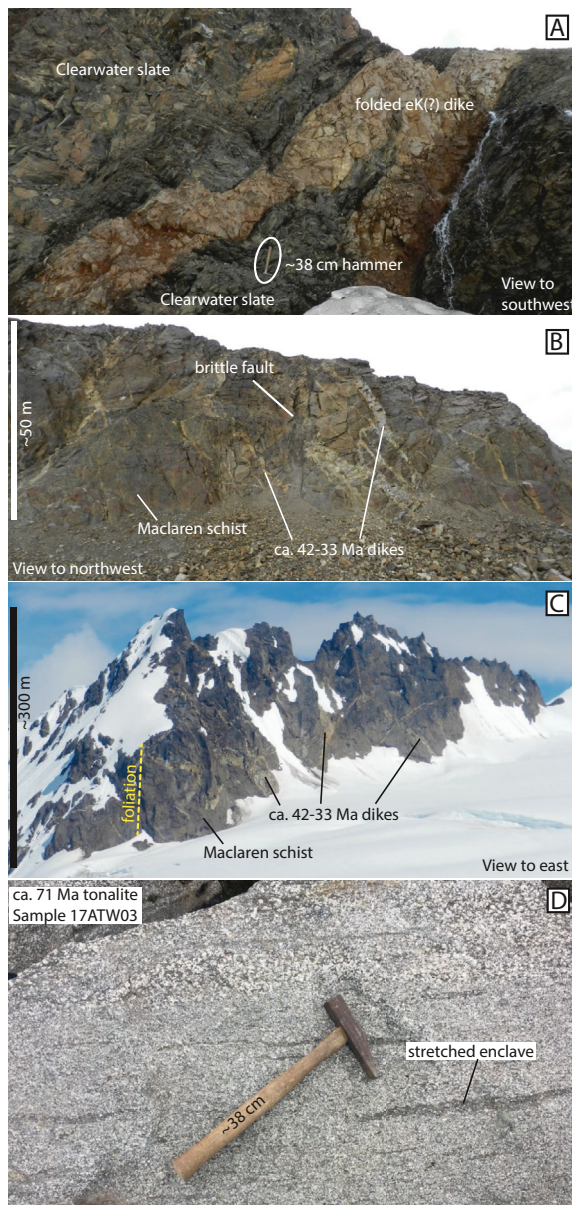


Figure 3. Field photos show key relationships in the area of Figure 2. (a) An intermediate dike associated with a zoned mafic-intermediate intrusion is folded with the foliation in the Clearwater slate. Photo is from an outcrop east of the middle fork of the Maclaren River. (b) Distributed brittle deformation is associated with the southern margin of the ca. 42–33 Ma plutonic suite. Nokleberg, Aleinikoff, Lange, et al. (1992) mapped this outcrop as an exposure of the Meteor Peak fault north of the Augustana Glacier. Dikes commonly cross-cut the metamorphic foliation in the Maclaren schist and are cut by small brittle faults. (c) Dikes associated with the ca. 42–33 Ma plutonic suite intersect the Maclaren schist foliation (yellow broken line) at multiple angles both south and north of the Meteor Peak fault. Photo is of an arête east of the Black Rapids Glacier. (d) Mafic enclaves in the ca. 74–65 Ma tonalite suite are highly stretched and commonly elongate in the down-dip direction. Photo is from sample location 17ATW03.

Along the west and middle forks of the Maclaren River, two approximately north-striking faults cut the dominant east-west structural fabric in the region. Although the faults are not exposed due to their location in the river valleys, their existence is implied by the misalignment of east-west-trending structures across the river valleys and the steep topographic gradient between the eastern Alaska Range and Susitna River valley.

A northeast-southwest-trending belt of topography separates the Maclaren River from the Susitna River valley (headwaters of Boulder Creek—Figure 2). Structures in the area include the Talkeetna fault and the herein-named Boulder Creek fault (BCF—Figure 2). The Talkeetna fault in the area is a steeply northwest-dipping structure exposed near the southeastern margin of the topography, which likely has limited Cenozoic slip, based on the modest offset of Late Cretaceous sedimentary rocks (Mooney, 2010; O'Neill et al., 2001). The map pattern suggests that the Boulder Creek fault dips steeply to the southeast and the topographic gradient across the fault trace marks the eastern boundary of the Susitna River valley. The Boulder Creek fault juxtaposes low-grade metagreywacke and slate of the Clearwater metasediments to the east against tonalite intrusions to the west (Figure 2). Thus, the southeast-side-up sense of slip on the Boulder Creek fault has cut out the higher-grade portion of the inverted metamorphic field gradient that is elsewhere present in the footwall of the Valdez Creek shear zone. Cataclastic deformation associated with the Boulder Creek fault overprints Late Cretaceous (e.g., Ridgway et al., 2002) ductile fabrics in the tonalite body, thus implying Cenozoic slip on the Boulder Creek fault. Although post-collisional brittle faults are present in the Clearwater Mountains to the southwest of the Boulder Creek fault (e.g., Mooney, 2010; Smith, 1981), the Valdez Creek shear zone does not appear to have experienced reactivation (e.g., Davidson et al., 1992) and is crosscut by the Boulder Creek fault (Figure 2).

4.1.2. Along-Strike Correlation of Structures

Published synthesis maps of the eastern Alaska Range have correlated the Valdez Creek shear zone in the west with a structure east of the Maclaren Glacier named the Meteor Peak fault (Wilson et al., 1998, 2015). The correlation appears to have stemmed from the location of the two structures at the southern margin of plutons within the Maclaren schist and the inference that all of the plutons in the area intruded at ca. 70 Ma (e.g., Aleinikoff et al., 1981; Nokleberg, Aleinikoff, Dutro, et al., 1992; Nokleberg, Aleinikoff, Lange, et al., 1992).

Multiple lines of evidence indicate that the Valdez Creek shear zone and Meteor Peak fault are not correlative structures. Mainly, the Cenozoic evolution of structures east of the Maclaren River reveals that the Valdez Creek fault formed as a reactivation of the Valdez Creek shear zone during the Oligocene (Waldien et al., 2021). Moreover, our observations of the Meteor Peak fault between the Black Rapids and Augustana Glaciers (BRG and AG—Figure 2) show it to be an anastomosing brittle fault system that follows the southern margin of the 42–33 Ma phase of the East Susitna batholith. Dikes along the margin of the 42–33 Ma composite pluton are generally offset by fewer than 10 m and cataclasis associated with slip on strands of the Meteor Peak fault is poorly developed and restricted to discrete zones less than 5 m wide (Figure 3b). These

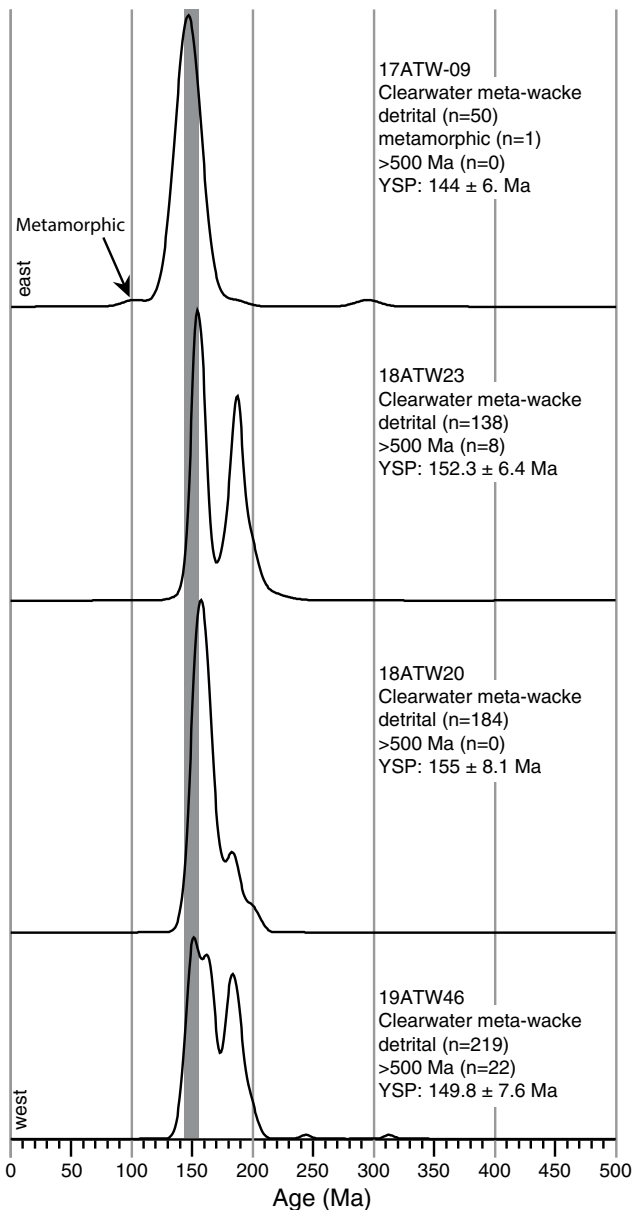


Figure 4. Kernel density estimate (KDE) plots of detrital zircon U-Pb age spectra (<500 Ma) for individual samples of Clearwater metagreywacke ordered from east (top) to west (bottom). The post-depositional metamorphic date is indicated for sample 17ATW-09. The dark gray bar at 155–144 Ma highlights the range of maximum depositional ages for individual samples. KDE plots were made using the DensityPlotter program (Vermeesch, 2012). YSP—weighted mean and 2 s uncertainty of the youngest statistical detrital population, interpreted as the maximum depositional age; n—number of analyses composing the plot.

observations together indicate that the Meteor Peak fault is a minor brittle fault that formed after ca. 33 Ma and thus is not related to the Late Cretaceous Valdez Creek shear zone.

After reconciling the structural complications near the headwaters of the Maclaren River described above, the along-strike continuity in metasedimentary belts reveals the transition between Cretaceous structures in the Clearwater Mountains and reactivated versions of those structures nearer to the Denali fault in the eastern Alaska Range (Figure 2). The Talkeetna-Broxson Gulch fault marks the boundary between the Wrangellia terrane and the Wrangellia-affiliated Clearwater metasediments. The Talkeetna fault in the Clearwater Mountains is a steeply dipping to sub-vertical crustal-scale fault with limited evidence for Cenozoic slip (Brennan et al., 2011; O'Neill et al., 2001). The Broxson Gulch fault in the Alaska Range is a moderately north-dipping reverse fault that is part of the post-32 Ma thrust system along the south flank of the Alaska Range (Waldien et al., 2021). The boundary between the Maclaren schist and Clearwater metasediments is the Valdez Creek shear zone in the west and Valdez Creek fault to the east. Late Cretaceous syn-collisional ductile thrusting is preserved in the Valdez Creek shear zone in the Clearwater Mountains (Davidson et al., 1992), whereas the shear zone has been reactivated as a brittle fault in the eastern Alaska Range (Waldien et al., 2021). The Meteor Peak fault appears to have no correlative structure in the Clearwater Mountains.

4.2. Zircon U-Pb Dating

4.2.1. Metasedimentary Rocks

Detrital zircon U-Pb age spectra from four samples of Clearwater metagreywacke (621 grains, Figure 4) are dominated by Jurassic grains. Three of the samples (18ATW20, 18ATW23, and 19ATW46) display bimodal distributions with modes at ca. 155 and 185 Ma. Pre-Jurassic grains in two of the samples define subordinate populations at ca. 550 Ma, 1,100–1,800 Ma, and 2,500–2,800 Ma. Sample 17ATW09 yielded a unimodal age peak centered at ca. 150 Ma. Maximum depositional ages of the samples range from ca. 155–144 Ma. Near the middle fork of the Maclaren River, sample 19ATW39 is a quartz-muscovite phyllite interfoliated with the Clearwater slate, which we interpret as a metamorphosed felsic tuff based on the composition and unimodal distribution of single-grain zircon dates, yielded a weighted mean age of 160.4 ± 1.5 Ma (Table 2).

Detrital zircon U-Pb age spectra from five samples of Maclaren schist (1,094 grains; Figure 5) display: (a) dominant Mesozoic age populations at ca. 110–85, 160–145, and 200–180 Ma, although the relative proportions vary; (b) a subordinate population of ca. 370–330 Ma grains; (c) Proterozoic and Archean grains in all samples, although abundances are low; (d) post-depositional metamorphic rims or recrystallized domains with dates of ca. 84–55 Ma (Supporting Information S1); and (e) mid-Cretaceous maximum depositional ages of ca. 91–88 Ma.

4.2.2. Plutonic Rocks

Multiple intrusive phases are present in the study area, each of which has a distinctive age-composition relationship that is unique to the thrust panels that host them. Here, we present the ages of the plutonic suites from structurally highest (youngest) to structurally lowest (oldest) level. The new ages are reported in Table 2 and Supporting Information S4 contains additional details.

Table 2
Igneous Zircon U-Pb Analytical Results

Host rocks	Sample name	Latitude (°N)	Longitude (°W)	Rock type	Weighted mean 206Pb/238U Age (Ma) ^a	MSWD	Number of acceptable grains in age calculation ^b	Total number of zircons analyzed ^c
Clearwater metasediments	19ATW39	63.3318	146.6695	Meta-felsic Tuff	160.4 ± 1.5	0.74	22	22
Maclaren schist	19ATW79	63.3548	146.6812	Quartz Monzonite	51.9 ± 0.6	3.2	45	53
Maclaren schist	19ATW40	63.4155	146.7800	Tonalite	64.6 ± 0.7	1.9	46	49
Maclaren schist	18ATW21	63.3070	146.9629	Tonalite	68.3 ± 1.3	3.7	33	40
Maclaren schist	17ATW03	63.2163	147.0698	Tonalite	70.5 ± 1.0	2.6	28	35
Maclaren schist	19ATW66	63.3473	146.8130	Biotite-garnet leucogranite	75.8 ± 1.9	1.14	9 ^d	29
Clearwater metasediments	19ATW55	63.2699	146.8861	Diorite	53.1 ± 0.6	0.71	16	21
Wrangellia terrane	14ATW50	63.2483	145.4092	Granodiorite	309.8 ± 3.9	3.2	30	32
Wrangellia terrane	17ATW11	63.3498	145.6523	Granodiorite	307.2 ± 6.1	0.9	12	14
Wrangellia terrane	16CSR17	63.3330	146.3319	Granite	306.3 ± 4.0	0.48	14	16
Wrangellia terrane	15DR140	63.3054	146.6025	Quartz syenite	144.1 ± 2.3	1.9	15	17
Wrangellia terrane	13ET270	63.2216	146.7085	Diorite	129.8 ± 2.4	1.5	31	31
Wrangellia terrane	19ATW81	63.2986	146.6962	Tonalite	112.9 ± 1.3	1.7	31	31

Note. MSWD, mean square weighted deviation.

^aWeighted mean uncertainties represent quadratic addition of internal and external uncertainties at 2s. ^bThe number of analyses that passed the filtering criteria. ^cThe total number of analyzed grains. ^dRim analyses: Filtering criteria relaxed to allow more analyses in age calculation.

Maclaren schist: The Maclaren schist hosts three intrusive suites that are distinguishable based on age and petrographic features. The youngest phase intruded the structurally highest portion of the Maclaren schist adjacent to the Denali fault. Compositions in this plutonic suite vary and include biotite tonalite, hornblende-biotite granodiorite, and biotite-muscovite granite. The margins of the bodies are zones of mutually crosscutting dikes that crosscut the metamorphic foliation in the Maclaren schist (Figure 3c). Many samples from the suite display a high-temperature fabric defined by the alignment of amphibole and plagioclase grains. Some samples display sub-solidus mylonitic fabrics. Samples from this suite yielded U-Pb zircon dates ranging from ca. 42 to 33 Ma (Benowitz et al., 2011; Regan et al., 2021).

An intermediate-age plutonic suite intruded the structurally lowest portion of the Maclaren schist in the Alaska Range and is cut by the Valdez Creek fault (Waldien et al., 2021). Plutons in this suite consist of non-foliated biotite or hornblende granodiorite with late biotite-muscovite-K-feldspar pegmatite veins. The margins of the plutons crosscut the Maclaren schist foliation (Waldien et al., 2021). One sample from this suite near the middle fork of the Maclaren River (19ATW79) yielded a U-Pb zircon weighted mean date of 51.9 ± 0.6 Ma.

The oldest intrusions in the Maclaren schist are tonalitic, found in the western portion of the study area near Boulder and Valdez Creeks (Figure 2), and generally contain a well-developed, high-temperature foliation defined by strained mafic enclaves and aligned biotite, plagioclase, and amphibole (Davidson et al., 1992; Figure 3d). The tonalite bodies display reaction textures wherein primary clinopyroxene has reacted to amphibole and then to biotite. Three samples from the tonalite suite yielded U-Pb zircon weighted mean dates of 64.6 ± 0.7 (19ATW40), 68.3 ± 1.3 (18ATW21), and 70.5 ± 1.0 Ma (17ATW03). In the headwaters of the west fork of the Maclaren River, the tonalite suite is associated with a garnet-and-biotite-bearing leucocratic body. The leucocratic body generally lacks internal structure and forms a series of disseminated veins and dikelets into the Maclaren schist along the margins. Zircon crystals separated from the leucocratic body (sample 19ATW66) display core-rim textures wherein the cores yield ages common of detrital zircons within the Maclaren schist and the rims yielded a weighted mean date of 75.8 ± 1.9 Ma.

Clearwater metasediments: Sample 19ATW55 came from a small (<50 m across) body of non-foliated hornblende diorite, which intrudes the Clearwater metasediments east of Boulder Creek and yielded a weighted

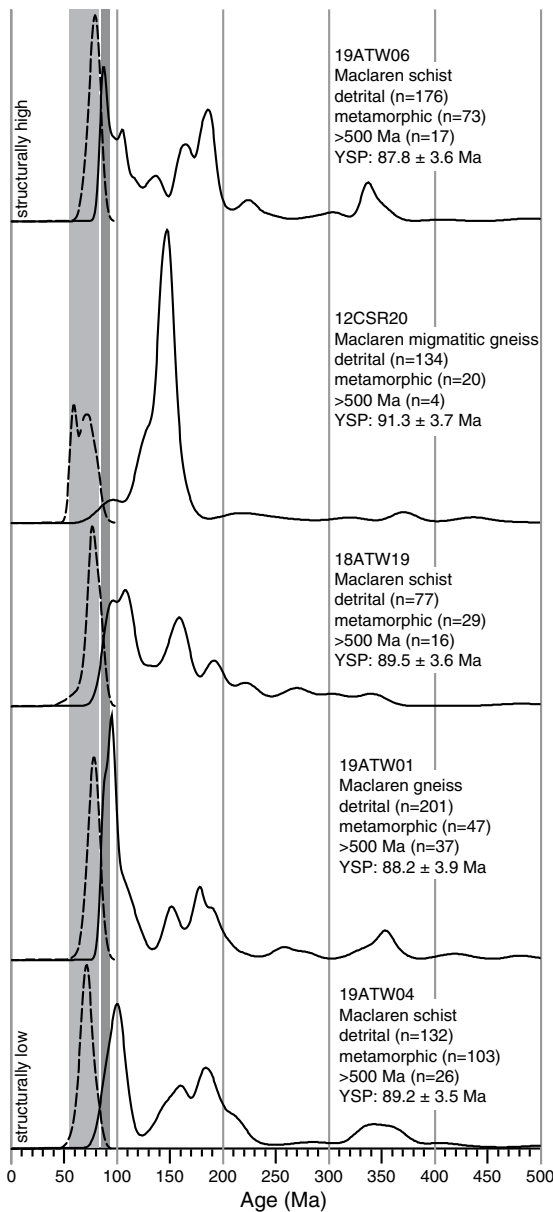


Figure 5. Kernel density estimate (KDE) plots of detrital zircon U-Pb age spectra (<500 Ma) for individual samples of Maclaren schist ordered from structurally highest (top) to structurally lowest (bottom). Post-depositional metamorphic dates are shown as a dashed line KDE curve and are outlined by a light gray bar at ca. 84–55 Ma. The dark gray bar at 91–87 Ma indicates the range of maximum depositional ages for individual samples in this study. KDE plots were made using the DensityPlotter program (Vermeesch, 2012). YSP—weighted mean and 2 s uncertainty of the youngest statistical detrital population, interpreted as the maximum depositional age; n—number of analyses in the plot.

rock weighted mean age), and 49.8 ± 0.3 Ma (15BG209—rhyodacite tuff, whole rock weighted mean age) (Table 3; Supporting Information S3).

mean date of 53.1 ± 0.6 Ma. The new date on sample 19ATW55 expands the known age range of small volume intrusions within the Clearwater metasediments, which elsewhere have been dated at ca. 142, 102, and 63–68 Ma (Davidson & McPhillips, 2007; Mooney, 2010; Waldien et al., 2021).

Wrangellia terrane: Our zircon U-Pb dating of plutonic rocks bears on two phases of magmatism within the Wrangellia terrane (Figure 2). The oldest dates come from a tabular granodiorite body east of the Delta River, which yielded weighted mean dates of 309.8 ± 3.9 Ma (14ATW50) and 307.2 ± 6.1 Ma (17ATW11). Similarly, a composite granodiorite-granite body near the Eureka Glacier (16CSR17) yielded a weighted mean date of 306.3 ± 4.0 Ma. Younger dates come from the Maclaren River corridor, where concentric diorite-granodiorite bodies with marginal diorite-gabbro dike systems intrude Skolai and Nikolai rocks. Samples from these bodies yielded weighted mean dates of 144.1 ± 2.3 Ma (15DR140—hornblende diorite body), 129.8 ± 2.4 Ma (13ET270—biotite granodiorite body), and 112.9 ± 1.3 Ma (19ATW81—hornblende diorite dike).

4.3. Hf Isotopic Signatures of Mesozoic Detrital Zircon Grains

Detrital zircon grains from both age populations in the Clearwater metasediments (ca. 155 and 185 Ma) display juvenile ϵ_{Hf} isotopic signatures (Figure 6). Zircon grains belonging to the Early Jurassic age population in sample 16ATW10 display ϵ_{Hf} values ranging from +4 to +11, whereas Early Jurassic grains in sample 15ATW23 have values of +5 to +16. Late Jurassic zircon grains in sample 16ATW10 yielded ϵ_{Hf} values ranging from +6 to +10 and sample 15ATW23 contains grains with values of +8 to +15.

Hf isotopic signatures from detrital zircon grains in the Maclaren schist (sample 15ATW29) show a range of juvenile and evolved ϵ_{Hf} compositions (Figure 6). Early Jurassic zircon grains display ϵ_{Hf} values ranging from –10 to +12. Late Jurassic grains are more juvenile and display ϵ_{Hf} values ranging from +2 to +15. The small population (three grains) of ca. 100 Ma zircon grains display a spread of ϵ_{Hf} values ranging from –18 to +13. Circa 90 Ma detrital zircon grains have more juvenile ϵ_{Hf} compositions ranging from +8 to +13.

4.4. $^{40}\text{Ar}/^{39}\text{Ar}$ Dates on Volcanic Strata

Volcanic strata overlap and are faulted against Paleozoic Wrangellia rocks along the southern margin of the Alaska Range east of the Delta River. The volcanic strata are generally felsic in composition, yet mafic flows, mafic dikes, and conglomeratic strata are found locally (Bond, 1976; Gillis et al., 2019; Hults & Athey, 2011; Waldien et al., 2018). Four felsic extrusive samples southeast of the Gulkana Glacier in our study area (Figure 2) yielded $^{40}\text{Ar}/^{39}\text{Ar}$ dates of 50.9 ± 0.5 Ma (12HODO—rhyodacite tuff, biotite plateau age), 45.5 ± 0.2 Ma (46GUNN—dacite flow, whole rock plateau age), 49.3 ± 0.7 Ma (15BG216—dacite flow, whole rock weighted mean age), and 49.8 ± 0.3 Ma (15BG209—rhyodacite tuff, whole rock weighted mean age).

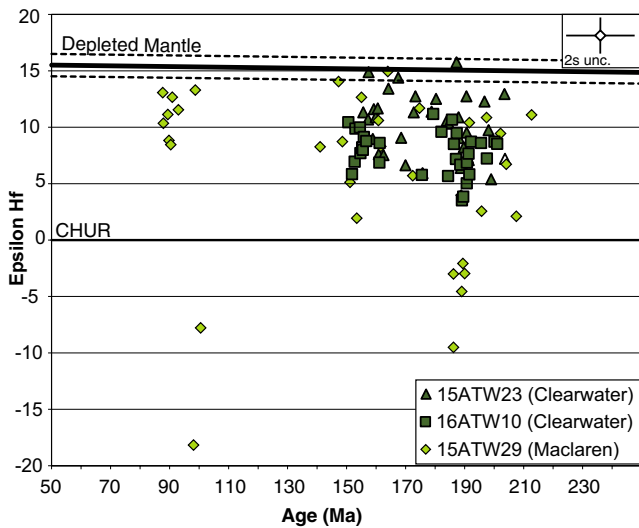


Figure 6. Epsilon (ϵ) Hf-versus-age plot of single grain analyses from the Maclaren schist and Clearwater metasediments (colored as in Figure 1). The maximum 2 s uncertainties (unc.) associated with the data points are represented by the data symbol in the upper right. CHUR—chondritic uniform reservoir.

5. Discussion

5.1. Protolith Provenance and Paleogeographic Setting for Metasedimentary Assemblages

5.1.1. Clearwater Metasediments

Detrital zircon U-Pb age spectra and Hf isotopic signatures suggest that the Clearwater metasedimentary rocks formed along the paleo-eastern margin of the Wrangellia composite terrane during the Late Jurassic-Early Cretaceous. Although terranes along the Laurentian margin contain Jurassic rocks that could have supplied Jurassic zircon grains to the Clearwater metasediment protolith (e.g., Allan et al., 2013; Gehrels et al., 2009; Sack et al., 2020), the general scarcity of pre-Mesozoic grains and juvenile ϵ Hf values of the Jurassic grains together suggest that the protolith sediment was derived from juvenile arc crust within the Wrangellia composite terrane (Figures 4 and 7). Jurassic source areas within the Wrangellia composite terrane include Chitina arc rocks (ca. 160–140 Ma: Beranek et al., 2017; Day et al., 2016; Roeske et al., 2003) and Talkeetna arc rocks (ca. 205–150 Ma: Amato et al., 2007; Rioux et al., 2007; Roeske et al., 1989). The maximum depositional ages of the Clearwater metasediments and the ages of inter-bedded volcanics indicate that the strata were deposited from ca. 160–144 Ma (Mooney, 2010; Table 2). Intrusion of a ca. 142 Ma alkali gabbro in the Clearwater Mountains post-dates deposition of the Clearwater protolith strata (Mooney, 2010; Figure 2).

Depositional ages, interpreted sediment source areas, detrital zircon Hf signatures, and stratigraphic features place the Clearwater metasediments among a suite of Late Jurassic-Early Cretaceous basinal assemblages that span the inboard (north and east in present coordinates) margin of the Wrangellia composite terrane from western Alaska to British Columbia. From west to southeast, these basinal assemblages include the Koksetna River sequence (Box et al., 2019; Hulst et al., 2013; Wallace et al., 1989), Clearwater metasediments (Mooney, 2010; Waldien et al., 2021; this study), Nutzotin Mountains sequence (Fasulo et al., 2020; Manuszak et al., 2007; Trop et al., 2020), Dezadeash Formation (Lowey, 2019), Vand Creek assemblage (Vice, 2017), and western Gravina belt (Yokelson et al., 2015). It is not necessary that these basinal assemblages were linked as a single basin system at the time of deposition (e.g., Hulst et al., 2013); however, the similarities in depositional setting and interpreted provenance within the Wrangellia composite terrane do suggest that they together represent a regionally extensive clastic marine sequence linked to the paleo-eastern margin of the Wrangellia composite terrane. An Early-to-mid-Cretaceous phase of strike-slip faulting may have translated the marine sequence relative to the Wrangellia composite terrane (e.g., Gehrels et al., 2009; McDermott et al., 2019; Mooney, 2010; Yokelson et al., 2015), yet the displacement history for that structure remains unclear.

Table 3
⁴⁰Ar/³⁹Ar Analytical Results for Volcanic Rocks

Sample name	Latitude (°N)	Longitude (°W)	Rock type	Phase analyzed	Grain size analyzed (μm)	Integrated age (Ma) ^a	Plateau age (Ma) ^a	Plateau information
12HODO	63.2233	145.4485	Rhyodacite tuff	Biotite	500–1000	50.9 ± 0.3	50.9 ± 0.5	6 of 12 steps 91.8% ³⁹ Ar release MSWD = 1.91
46GUNN	63.2108	145.4025	Dacite flow	Whole rock	212–500	45.1 ± 0.1	45.5 ± 0.2	3 of 8 fractions 49.7% ³⁹ Ar release MSWD = 1.55
15BG216	63.2098	145.3516	Dacite flow	Whole rock	212–500	48.8 ± 0.4	49.3 ± 0.7 ^b	7 of 8 fractions 94% ³⁹ Ar release MSWD = 3.34
15BG209	63.2123	145.3635	Rhyodacite tuff	Whole rock	212–500	49.6 ± 0.4	49.8 ± 0.3 ^b	2 of 8 fractions 50.8% ³⁹ Ar release MSWD = 3.18

Note. MSWD, mean square weighted deviation.

^aUncertainties are 1s. ^bDid not meet all the criteria of a plateau age, hence a weighted average age is presented.

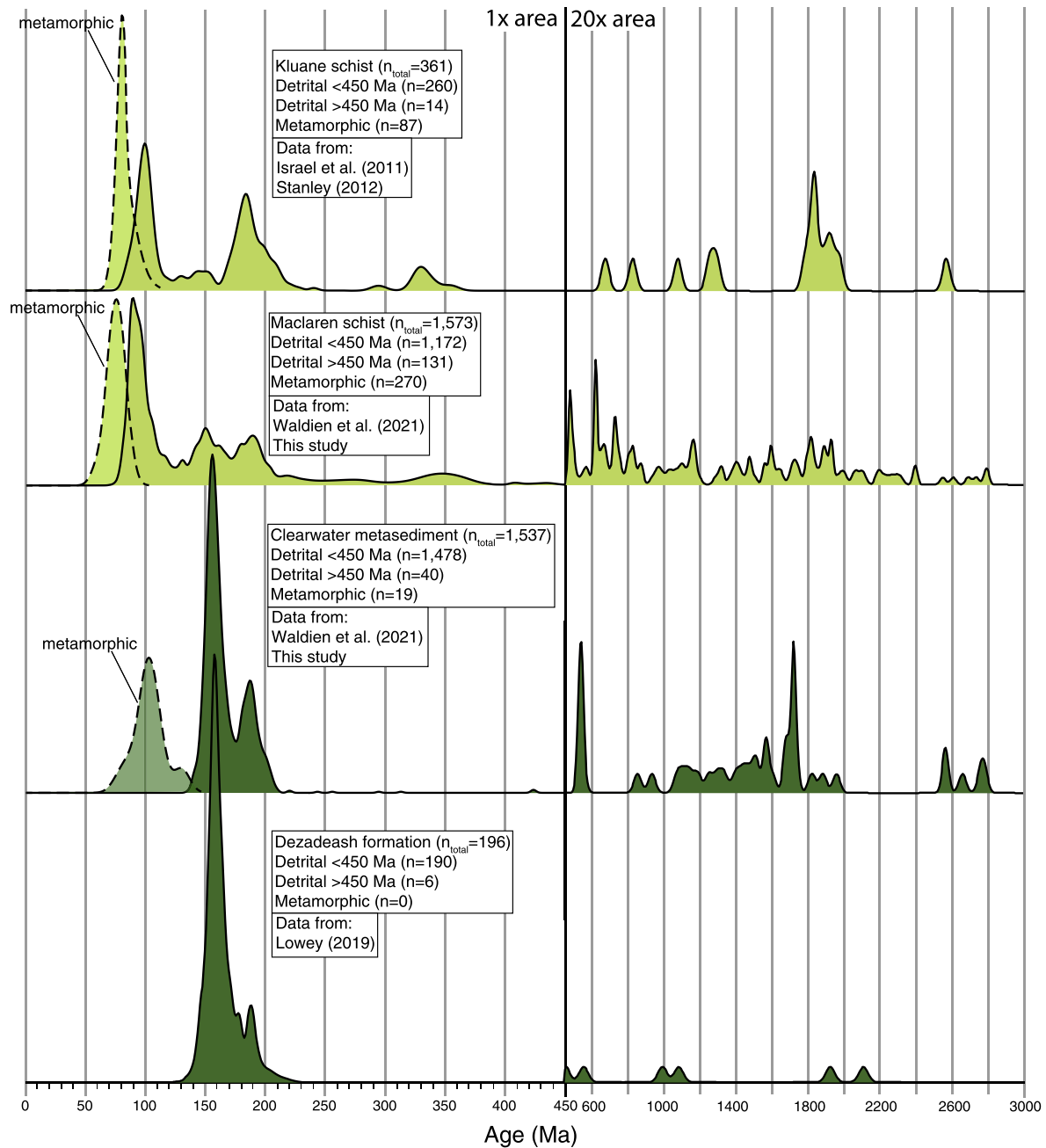


Figure 7. Kernel density estimate (KDE) plots of compiled detrital zircon U-Pb age spectra for the Maclaren schist, Kluane schist, Clearwater metasediments, and Dezadeash Formation, colored as in Figure 1. Note the change in horizontal scale and the 20× increase in area under the curves at 450 Ma. The dashed line KDE curves represent post-depositional metamorphic grains, which are plotted at half the vertical scale of the <450 Ma detrital age spectra. KDE plots were made using the DZStats and Density Plotter programs (Vermeesch, 2012; Saylor & Sundell, 2016).

5.1.2. Maclaren Schist

Detrital zircon U-Pb age spectra indicate that the protolith of the Maclaren schist was deposited into a basin between previously accreted Cordilleran terranes to the east and the Wrangellia composite terrane to the west at ca. 94–86 Ma. As with other detrital zircon U-Pb studies of the Maclaren schist (Link, 2017; Waldien et al., 2021), the samples presented herein comprise dominant detrital age populations at ca. 100–85, 200–145, and 370–330 Ma (Figures 5 and 7). The ubiquitous presence of pre-Mesozoic grains suggests that the protolith strata received sediment from regions within the Yukon-Tanana terrane and parautochthonous

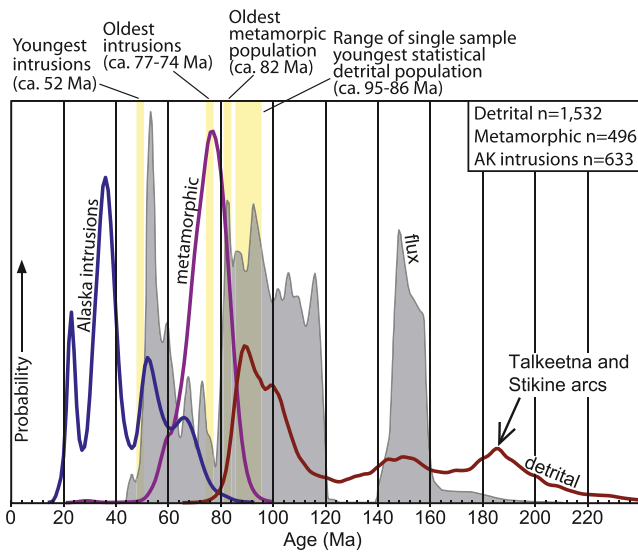


Figure 8. Probability density plot comparing ≤ 240 Ma detrital (dark red curve) and metamorphic (purple curve) U-Pb zircon dates from the Maclaren-Kluane schist (this study; Israel et al., 2011; Stanley, 2012; Waldien et al., 2021) with the 240–40 Ma magmatic flux curve of the central Coast Mountains arc (filled gray curve; from Gehrels et al., 2009). LA-ICPMS dates from plutonic rocks within the Maclaren and Cottonwood schists constitute the blue curve (this study; Regan et al., 2021). The vertical yellow bars highlight important time periods that are shared in the evolution of the Maclaren-Kluane schist and associated batholithic rocks. Note how magmatism within the Maclaren and Cottonwood schists (Alaska intrusions) outlasts the shared magmatism. n—number of grains used to generate each curve.

North America (e.g., Dusel-Bacon & Williams, 2009; Dusel-Bacon et al., 2017; Gehrels & Pecha, 2014; Pecha et al., 2016; Piercey & Colpron, 2009). The overlap between periods of high magmatic flux in the Coast Mountains arc and the populations of detrital zircon grains in the Maclaren schist further suggests that the protolith sediment was sourced from rocks along the western margin of North America (Figure 8). Hf isotopic compositions from Mesozoic zircon grains in the Maclaren schist display a range of juvenile and evolved ϵ_{Hf} values that may record either isotopic heterogeneity in the peri-continental source area (e.g., Cecil et al., 2011; Piercy et al., 2003; Sack et al., 2020), sediment sourced from igneous belts built upon both the Wrangellia composite terrane and the North American margin, and/or sediment recycling from the Clearwater metasediments. All samples presented in this study display a population of metamorphic growth rims dated at ca. 84–55 Ma, which we interpret to post-date deposition (Figures 5 and 7; Supporting Information S1).

The Maclaren schist displays both similarities and differences compared to other Mesozoic basinal assemblages in the suture zone between the Wrangellia composite terrane and the Mesozoic North American margin. Ca. 110–90 Ma strata are exposed in the northern domain of the Kahiltina assemblage throughout the central and western Alaska Range (Box et al., 2019; Hampton et al., 2007, 2010; Hults et al., 2013; Kalbas et al., 2007; Romero et al., 2020). The eastern Gravina belt of southeastern Alaska contains similar continental-derived strata, yet detrital zircon age spectra and available biostratigraphic information suggest the strata were deposited at ca. 120–110 Ma (Berg et al., 1972; Kapp & Gehrels, 1998; Yokelson et al., 2015). The Maclaren schist, northern Kahiltina, and eastern Gravina assemblages all share a ca. 120–100 Ma detrital zircon age population that, in addition to Precambrian grains, likely records a sediment source from igneous belts corresponding to the Teslin, Whitehorse, and Coffee Creek plutonic suites built upon the western margin of North

America (Allan et al., 2013; Tempelman-Kluit & Wanless, 1975). The additional presence of Jurassic age populations with juvenile ϵ_{Hf} signatures in these basin assemblages permits sediment input from approaching outboard terranes as the marine basin closed. The Maclaren schist, however, differs from much of the northern Kahiltina and eastern Gravina strata in that it is 10–30 Myr younger and experienced amphibolite facies metamorphism during the collision of the Wrangellia composite terrane. The sum of information suggests that the protolith of the Maclaren schist formed in one of the youngest, if not the youngest, known syn-collisional marine basins between the Wrangellia composite terrane and North American margin.

5.2. Correlative Rock Packages and Strike-Slip Separation

Our restoration of the Denali fault system relies on the correlation of metasedimentary, plutonic, and volcanic belts across the fault. The correlative rock packages are listed in Table 1, located as boxed numbers in Figure 1, and described below.

5.2.1. Clearwater-Nutzotin-Dezadeash (Meta)Sedimentary Strata

Our new data from the Clearwater metasediments suggest that they correlate with the Nutzotin Mountains sequence and Dezadeash Formation. Presently, the Clearwater metasediments are exposed south of the Denali fault in the eastern Alaska Range, the Nutzotin Mountains sequence is exposed south of the Denali fault and east of the Totschunda fault in eastern Alaska, and the Dezadeash Formation is exposed the northeast of the Denali fault in southwestern Yukon (Figure 1). A correlation between the Dezadeash and Nutzotin strata was initially proposed based on age and sedimentological features that are shared between the two successions (Eisbacher, 1976). Later work by Lowey (1998) documented the existence of a paleochannel carrying distinctive limestone boulders incised into the Dezadeash and Nutzotin strata, which has been offset ~370 km by the Denali fault. More recent studies involving detrital zircon U-Pb

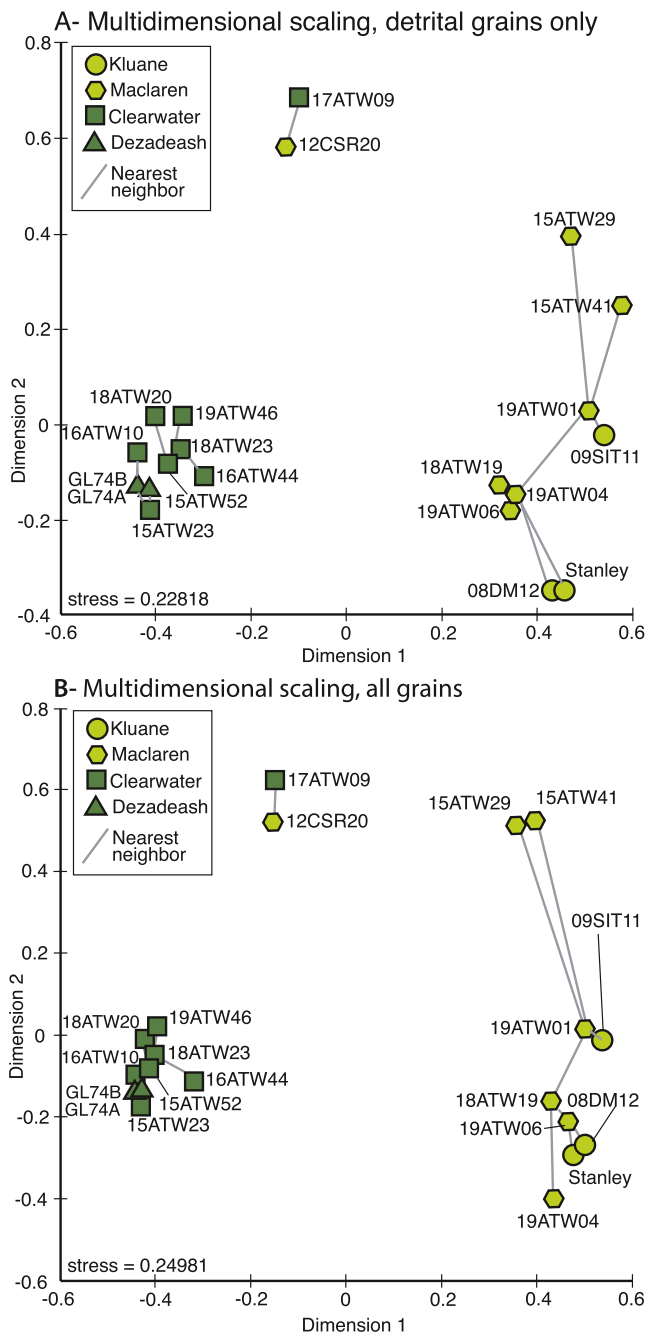


Figure 9. Multidimensional scaling (MDS) plots of U-Pb age spectra from individual samples of Maclaren schist (hexagons), Kluane schist (circles), Clearwater metasediments (squares), and Dezadeash Formation (triangles). All symbols are colored to match map units in Figure 1. (a) MDS of U-Pb age spectra excluding post-depositional metamorphic grains. (b) MDS of U-Pb age spectra including post-depositional metamorphic grains. MDS plots were made using the DZmids program of Saylor et al. (2018). Maclaren and Clearwater data are from this study and Waldien et al. (2021); Kluane data are from Israel et al. (2011) and Stanley (2012); Dezadeash data are from Lowey (2019).

dating show similar age populations and distribution of Jurassic and Early Cretaceous zircon grains within the Dezadeash Formation, Nutzotin Mountains sequence, and Clearwater metasediments, which are interpreted to be sourced from Jurassic arcs built upon the Wrangellia composite terrane (Fasulo et al., 2020; Link, 2017; Lowey, 2019; Manuszak et al., 2007; Mooney, 2010; Trop et al., 2020; Waldien et al., 2021). Among the dated samples, the Dezadeash Formation and Clearwater metasediments of the Alaska Range show the greatest similarity because they both include a ca. 185 Ma age population that is absent from the Nutzotin strata and Clearwater metasediments of the Clearwater mountains (cf., Fasulo et al., 2020; Lowey, 2019; Mooney, 2010; Trop et al., 2020; Figures 7 and 9). Hf isotopic signatures from detrital zircon grains in the Clearwater metasediments show juvenile ϵ_{Hf} values (Figure 6), which compare well with juvenile whole rock ϵ_{Nd} values from the Dezadeash Formation (Lowey, 2011) and juvenile zircon ϵ_{Hf} values from age-equivalent detrital zircon grains in the Nutzotin Mountains sequence (Fasulo et al., 2020). Biostratigraphic and U-Pb radioisotopic ages indicate that Clearwater-Nutzotin-Dezadeash rocks were deposited from ca. 160 to 135 Ma (Fasulo et al., 2020; Lowey, 2011; Mooney, 2010; Trop et al., 2020; Figure 4).

Because the Clearwater, Nutzotin, and Dezadeash rocks are presently separated from each other along the Denali fault system, their restoration requires slip on both the Denali fault and Totschunda fault. The incised paleochannel records ~370 km of dextral separation between the Dezadeash Formation and Nutzotin Mountains sequence (Lowey, 1998). The measured 80–90 km of separation between the Clearwater and Nutzotin strata likely resulted from right-lateral slip transfer from the Totschunda fault to the Denali fault (e.g., Berkelhammer et al., 2019; Brueseke et al., 2019; Waldien et al., 2018). Cumulative translation and dissection of the Clearwater, Nutzotin, and Dezadeash assemblages record at least 465 km of separation on the Denali fault.

5.2.2. Alaska-Type Ultramafic Intrusions

Ultramafic-to-intermediate intrusive bodies within the Clearwater metasediments (AK) and Dezadeash Formation (YT) correlate based on petrography and possibly age. Early workers in both the Clearwater metasediments and Dezadeash Formation had described pegmatitic biotite-hornblende clinopyroxenite cumulate bodies associated with granodiorite (Eisbacher, 1976; Stout, 1965). Subsequent work established that these bodies display geochemical characteristics that classify them as Alaska-type zoned ultramafic suites (Sturrock et al., 1980; Waldien et al., 2021). In Yukon, the Pyroxenite Creek ultramafite and associated Shorty Creek granodiorite hosted within the Dezadeash Formation yielded amphibole and biotite K-Ar dates ranging from ca. 126 to 106 Ma (Eisbacher, 1976). In the Alaska Range, petrographically similar biotite-hornblende clinopyroxenite cumulates and associated granodiorite bodies intrude the Clearwater metasediments north of Ann Creek and have been dated at ca. 102 Ma (Stout, 1965; Waldien et al., 2021). Due to similarities in petrography, structural position, host rocks, proximity to the Denali fault, and general age information, it is possible that the Pyroxenite Creek and Ann Creek zoned ultramafic bodies represent a single body that was dissected by the Denali fault. If correlative, the bodies would record up to 505 km of dextral separation across the Denali fault.

5.2.3. Maclaren-Kluane Schist

The Maclaren schist (AK) and Kluane schist (YT) correlate based on petrography, metamorphic history, and detrital zircon U-Pb age spectra (Figures 7 and 9). Both schist bodies display a dominant foliation that dips toward North America (north or northeast). The foliation in both bodies contains porphyroclasts of garnet and distinctive “black” plagioclase, both of which contain curved inclusion trails defined by rutile and graphite (Mezger, Chacko, et al., 2001; Stanley, 2012; Waldien et al., 2021). The shared metamorphic history involves an early Barrovian series path that peaked at Temperature (T) $\sim 500^{\circ}\text{C}$ and Pressure (P) ≥ 7 kbar, followed by a phase of isothermal decompression, and subsequent Buchan series conditions of $T \sim 550\text{--}750^{\circ}\text{C}$ and $P \leq 5$ kbar (Davidson & McPhillips, 2007; Mezger, Chacko, et al., 2001). In the Alaska Range, the eastern portion of the Maclaren schist experienced a post-32 Ma retrograde metamorphic event that has been linked to the reactivation of adjacent structures (Waldien et al., 2021). The absence of the retrograde event in the Kluane schist does not preclude the correlation because the retrogression took place after the bodies were separated by the Denali fault (see Section 5.3). Detrital zircon age spectra from the Maclaren and Kluane schists both contain a predominance of Mesozoic grains accompanied by smaller Paleozoic and Precambrian populations and metamorphic overgrowth rims ranging in age from ca. 84 to 55 Ma (Figures 7 and 9). All published detrital zircon U-Pb data sets yield maximum depositional ages between 95 and 86 Ma (Figure 5; Supporting Information S2). Because each schist body is cut obliquely by the Denali fault and no discrete diagnostic feature within the schists has been found for correlation, the measurement of strike-slip separation between the bodies is approximate. However, measuring from center to center of the cut face of each body yields ~ 445 km of dextral separation.

5.2.4. East Susitna-Ruby Range Batholith (74–57 Ma Phase)

Late Cretaceous and Paleocene plutonic belts within the Maclaren and Kluane schists have similar ages and compositions. Both comprise predominantly Late Cretaceous tonalite and Paleocene granodiorite, although their proportions differ. In the East Susitna batholith (AK), syn-collisional tonalite bodies dated at ca. 74–65 Ma represent the oldest phase of magmatism within the Maclaren schist (Aleinikoff et al., 1981; Ridgway et al., 2002; this study). The oldest dated rocks within the Ruby Range batholith (YT) come from intermediate and mafic intrusions dated at 72–68 Ma (Israel et al., 2011), and possibly as old as 77 Ma (Stanley, 2012). Voluminous ca. 64–57 Ma granodiorite-to-granite plutons compose the main phase of the Ruby Range batholith (Israel et al., 2011). Granodiorite bodies dated at ca. 57 Ma represent a volumetrically minor portion of the East Susitna batholith (Riccio et al., 2014; Figure 2), but are present throughout the Talkeetna Mountains to the west (Csejtey et al., 1992). Although the proportions of each magmatic phase do not appear to be equal within the East Susitna and Ruby Range batholiths, the range of ages and compositions of the intrusions are nearly identical. It remains unclear if there are individual bodies in the dissected 74–57 Ma batholith that can be matched across the Denali fault, yet correlating the easternmost 57 Ma pluton south of the Denali fault in Alaska to the northwestern margin of the Ruby Range batholith in Yukon results in a minimum dextral separation of 425 km.

5.2.5. Shakwak-Ann Creek Pluton (52–48 Ma)

Early Eocene plutonic rocks hosted within the Maclaren and Kluane schists correlate based on structural position, composition, and age. In Yukon, the Hayden Lake plutonic suite comprises ca. 55–48 Ma felsic plutons intruded into the structurally lowest portion of the Kluane schist (Colpron et al., 2016; Stanley, 2012). Similar plutons in Alaska include the ca. 52 Ma biotite granodiorite-monzonite plutons north of Ann Creek and in the west fork of the Maclaren River (Figure 2). The westernmost pluton within the Hayden Lake suite (Shakwak pluton) is a $>54\text{--}46$ Ma (K-Ar biotite cooling and U-Pb zircon crystallization dates, respectively) composite body consisting of unfoliated biotite tonalite, biotite granodiorite, and quartz diorite (Yukon Geological Survey, 2020). Due to the overlap in age, identical structural position, overlapping rock types, and proximity to the Denali fault, we propose a correlation between the Shakwak pluton and the ca. 52 Ma biotite quartz monzonite body north of Ann Creek. Matching these two igneous bodies results in ~ 465 km of dextral separation along the Denali fault. We regard this correlation as our highest quality match across the Denali fault and the most accurate measurement of strike-slip separation.

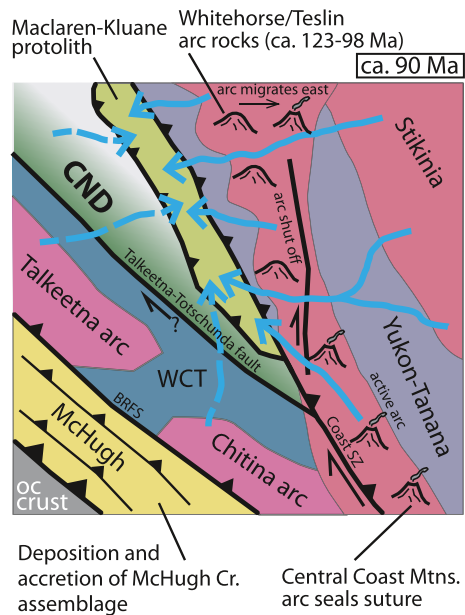


Figure 10. Schematic map view diagram illustrating the interpreted tectonic setting of the Maclaren-Kluane protolith basin. Sediment was delivered to the basin by drainage systems (blue lines/arrows; dashed lines where uncertain) that sourced uplifted terranes to the east, south, and possibly the west. Strike-slip fault systems in the Coast shear zone (Coast SZ) and on both sides of the Maclaren-Kluane basin have been documented to be active at this time. Deposition and accretion of the McHugh Creek assemblage record ongoing subduction along the outboard margin of the Wrangellia composite terrane. Map unit colors are the same as Figure 1. WCT—Wrangellia composite terrane; CND—Clearwater-Nutzotin-Dezadeash assemblage; oc—oceanic; BRFS—Border Ranges fault system.

5.2.6. Paleogene Volcanic Rocks

Post-collisional volcanic strata may correlate based on composition, structural setting, and general age information. South of the Denali fault, ca. 51–46 Ma volcanic strata between the Delta and Chistochina Rivers (Figure 1) in Alaska consist predominantly of syn-extensional felsic tuffs with lesser basalt-to-andesite flows and dikes (Bond, 1976; Gillis et al., 2019; Waldien et al., 2018; Figure 2 and Table 3). The volcanic rocks near the Chistochina River appear to be the eastern-most isolated extent of the Paleogene volcanic belt that covers much of the Talkeetna Mountains (Csejtey et al., 1978, 1992; Nokleberg, Aleinikoff, Lange, et al., 1992). Potentially correlative rocks northeast of the Denali fault in southwestern Yukon include graben-bounded rhyolite tuffs with lesser andesite and basalt (Colpron et al., 2016; Miskovic and Francis, 2004). Field relationships and radiometric ages link the volcanic rocks to the ca. 57–55 Ma plutonic suite throughout southwestern Yukon (Israel et al., 2011; Miskovic & Francis, 2004; Morris & Creaser, 2003). The Bennett Lake igneous complex near the Yukon-British Columbia border, however, contains lava flows as young as ca. 50 Ma (Morrison et al., 1979; Morris & Creaser, 2003). Although no unique correlation between Eocene volcanic complexes across the Denali fault has yet been identified, we propose that the ca. 50 Ma volcanic strata and intrusions in the eastern Alaska Range may be a displaced portion of the Bennett Lake igneous complex or a suite of distal channelized flows. Moreover, the northern Talkeetna Mountains west of our study area contain a suite of ca. 63–50 Ma bimodal volcanic strata and associated intrusions (Cole et al., 2007; Csejtey et al., 1992), which may correlate with the Rhyolite Creek volcanics and associated intrusions north of the Ruby Range batholith in Yukon. If correlative, the volcanic fields could record up to 580 km of separation on the Denali fault, yet the combined likelihood that the flows were channelized and uncertainties in Eocene geomorphology of the region make this measurement speculative. The potential correlation raises the possibility that mineralization associated with the Eocene volcanic strata in Canada may

also be present in the Alaskan volcanic rocks (e.g., Light et al., 1990), but more field-based geochemical and geochronological studies of Paleogene volcanic rocks in the Alaska Range and Talkeetna Mountains will be necessary to vet these hypotheses.

5.3. Palinspastic Reconstruction

The Maclaren-Kluane schist and associated rocks record nearly 100 Myr of tectonic evolution in the North American Cordillera. Our palinspastic reconstruction of the Denali fault begins with deposition of the Maclaren-Kluane protolith in the mid-Cretaceous and culminates with historic dextral slip in the Denali fault system. In addition to our data highlighting the total offset history on the modern Denali fault, we use markers established by Regan et al. (2021) to restore the post-33 Ma slip (Table 1).

Ca. 95–82 Ma (Figure 10): The protolith of the Maclaren-Kluane schist was deposited into a marine basin west of the Coast Mountains arc. Sediment was delivered to the basin from uplifted regions to the east, south, and possibly the west. Due to stratigraphic, structural, and thermochronological evidence for Early-to-mid-Cretaceous oblique shortening in the region (e.g., Johnston, 1999; Mair et al., 2006; McDermott et al., 2019; Ridgway et al., 2002), it is likely that the Maclaren-Kluane protolith was deposited in a contractional setting. We infer that syn-depositional imbrication of the Maclaren-Kluane protolith took place along east-dipping structures because the prograde structures within the Maclaren-Kluane schist dip north and east toward the North American continent (Davidson et al., 1992; Erdmer & Mortensen, 1993; Johnston & Canil, 2007; Lowey, 2000) and the timing of protolith deposition overlaps with an eastward migration of arc magmatism across the present-day southwestern Yukon (cf. Allan et al., 2013; Hart et al., 2004;

Tempelman-Kluit & Wanless, 1975). Taken together, these data suggest that the Maclaren-Kluane protolith sediment formed in a contractional forearc position during the waning stage of the west-facing mid-Cretaceous arc built upon the Yukon-Tanana terrane. Maximum depositional ages from the Maclaren schist require that final closure of the forearc basin and associated tectonic underplating of the Maclaren-Kluane schist took place after ca. 86 Ma.

It remains unclear whether Late Cretaceous syn-collisional underplating of the Maclaren-Kluane schist requires a subduction zone between the Wrangellia composite terrane and the North American margin at that time. Hypotheses regarding the nature of the crust along the inboard margin of the Wrangellia terrane in the mid-to-Late Cretaceous include oceanic crust, a thickened oceanic(?) plateau, or a combination of these end-member scenarios (e.g., Lowey, 2019; Trop & Ridgway, 2007; Waldien et al., 2021). The presence of oceanic crust is implied by the apparently disparate geologic histories between the paleo-eastern margin of the Wrangellia composite terrane and western margin of North America prior to collision in the mid-Cretaceous (Trop et al., 2020). Alternatively, it has been suggested that the Early Cretaceous collision of the Wrangellia composite terrane with western North America was followed by transtensional rifting that reopened the marine basin (McClelland et al., 1992), yet it is not clear if the rift basins evolved to full seafloor spreading. An argument against the presence of a wide marginal seaway between the Wrangellia terrane and North America draws on the presence of an Early-to-mid-Cretaceous magmatic belt in Yukon (Whitehorse, Dawson Range, Tombstone suites) and lack of mid-Cretaceous arc rocks south of the Maclaren schist in southern Alaska. Because deposition and accretion of the McHugh Creek Assemblage record paleo-east-dipping subduction along the western margin of the Wrangellia composite terrane from ca. 100–90 Ma (Amato & Pavlis, 2010; Amato et al., 2013), the singular magmatic belt in Yukon could be explained by that subduction zone alone, and eastward migration of the arc magmatism across Yukon could be attributed changes in the geometry of that slab leading up to underplating of the Maclaren-Kluane schist and cessation of arc magmatism between ca. 83 and 78 Ma (e.g., Gehrels et al., 2009; Figure 8). If a second subduction zone were present between the Wrangellia composite terrane and the North American margin, then two sub-parallel mid-Cretaceous igneous belts should be present. Acknowledging the aforementioned uncertainties regarding the nature of the crust beneath the mid-to-late Cretaceous marginal seaway between the Wrangellia composite terrane and western North America, we drafted Figure 11 to include queried oceanic crust along the eastern margin of the Wrangellia composite terrane.

Ca. 82–65 Ma (Figure 11a): Tectonic underplating of the Maclaren-Kluane schist beneath the western margin of North America resulted in Barrovian series metamorphism that began shortly after deposition. During underplating, the schist experienced kyanite grade conditions (e.g., Davidson et al., 1992; Mezger, Chacko, et al., 2001) and growth of ca. 82 Ma metamorphic zircon rims.

In Yukon, the structure responsible for burial and metamorphism of the Kluane schist is largely overprinted by the Ruby Ranges batholith (e.g., Israel et al., 2011). Along strike to the south of Kluane Lake, the Kluhini River shear zone has been described as an east-dipping shear zone that thrusts the Yukon-Tanana terrane and related igneous belts over pelitic gneiss with an Early Cretaceous protolith age (Vice, 2017). In Alaska, a structure beneath the Susitna Glacier (SGTF—Figure 2) places pre-Jurassic continental margin rocks hosting ca. 98 Ma plutons in the north against the Maclaren schist and East Susitna batholith in the south (Figure 2). We infer that historic and Neogene slip on the Susitna Glacier thrust fault reactivated a Mesozoic collisional structure correlative with the Kluhini River shear zone.

Following underplating, shortening continued by the formation of the Valdez Creek-Tatshenshini shear zone along the former plate boundary between the Maclaren-Kluane schist to the northeast and the Clearwater-Nutzotin-Dezadeash strata to the southwest (Waldien et al., 2021). Our date of ca. 76 Ma on the garnet-biotite leucocratic body within the Maclaren schist suggests that initiation of slip on the Valdez Creek shear zone may have facilitated decompression partial melting in the schist or served as a conduit for melt migration (e.g., Hollister, 1993). Shortening along the Valdez Creek-Tatshenshini shear zone developed an inverted metamorphic field gradient preserved in the footwall Clearwater-Dezadeash metasediments, which reached peak upper greenschist-lower amphibolite facies conditions at ca. 65 Ma (Lowey, 2000; Waldien et al., 2021).

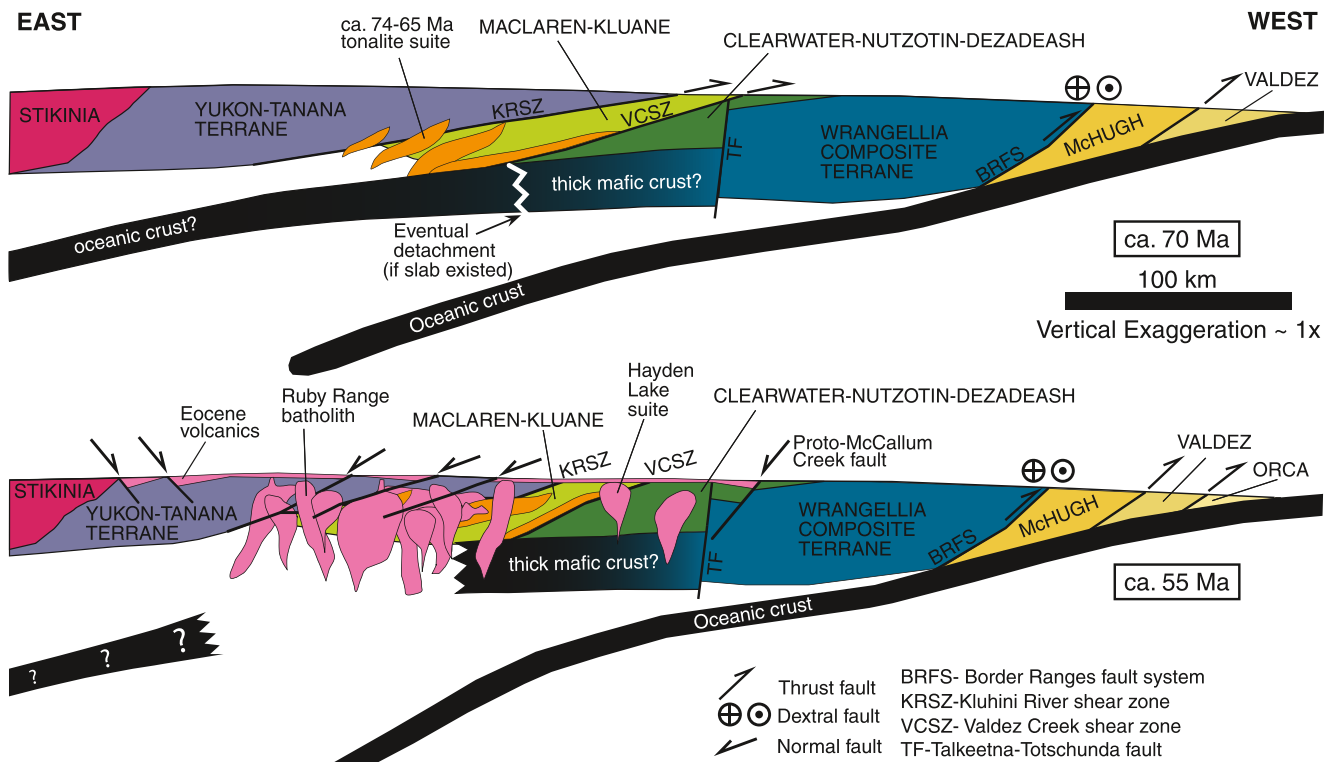


Figure 11. Schematic cross-sections illustrating generalized crustal structure during syn-collisional metamorphism of the Maclaren-Kluane schist. Colors are the same as Figure 1. (a) From ca. 74 to 65 Ma the Maclaren-Kluane schist underwent regional amphibolite facies metamorphism contemporaneous with slip on the Valdez Creek shear zone and syn-kinematic intrusion of tonalite bodies. Oceanic lithosphere may have been attached to the inboard margin of the Wrangellia composite terrane, but subduction in the marginal seaway is not necessary to explain regional magmatism. Deposition and accretion of the Valdez Group record ongoing subduction along the outboard margin of the Wrangellia composite terrane. (b) From ca. 60 to 50 Ma the Maclaren-Kluane schist experienced regional high temperature-low pressure metamorphic conditions contemporaneous with regional extension and intrusion of the main voluminous phase of the Ruby Range batholith. If oceanic lithosphere were attached to the inboard margin of the Wrangellia composite terrane, it likely would have detached by this time. Deposition and accretion of the Orca Group record ongoing subduction along the outboard margin of the Wrangellia composite terrane.

Ca. 60–50 Ma (Figure 11b): Cessation of slip on the Valdez Creek-Tatshenshini shear zone was followed by isothermal decompression throughout much of the Maclaren-Kluane schist (Mezger, Chacko, et al., 2001), local cooling near the Valdez Creek shear zone in the Clearwater Mountains (AK) (Ridgway et al., 2002), and reheating associated with voluminous magmatism in the Ruby Range batholith in Yukon (Israel et al., 2011; Mezger, Chacko, et al., 2001). The magmatism was accompanied by regional extension, which preserved volcanic strata within grabens throughout eastern Alaska, southwestern Yukon, and northern British Columbia (Bacon et al., 1990; Miskovic and Francis, 2004; Morris & Creaser, 2003). South of the Denali fault in Alaska, syn-extensional volcanic strata and intrusions near the Gulkana Glacier record formation of the McCallum Creek fault as part of the Paleogene extensional system (Gillis et al., 2019; Terhune et al., 2015; Figure 12a). Despite the regional importance of Paleogene extension, eastern Alaska and southwestern Yukon appear not to have experienced the high magnitude of extension that occurred in coeval extensional systems farther south in the Cordillera (e.g., Parrish et al., 1988). The ca. 60–50 Ma syn-extensional volcanism may record the initiation of dextral motion along the modern Denali fault in concert with dextral-slip on the Tintina and Border Ranges fault systems during oblique subduction of a spreading center along the outboard margin of the Wrangellia composite terrane (Davidson & Garver, 2017; Gabrielse et al., 2006; Roeske et al., 2003). However, our correlation of the Shakwak and Ann Creek plutons asserts that localization of the modern Denali fault and subsequent dissection of the Maclaren-Kluane schist and the associated batholith is restricted to post-52 Ma (Figure 12a).

Ca. 33 Ma (Figure 12b): The ca. 42–33 Ma phase of the East Susitna batholith (AK) and absence of age-equivalent plutons in the Ruby Range batholith (YT) support our hypothesis of localized dextral slip on the Denali fault by ca. 42 Ma (see also Figure 8). The 42–33 Ma plutons within the Maclaren schist constitute

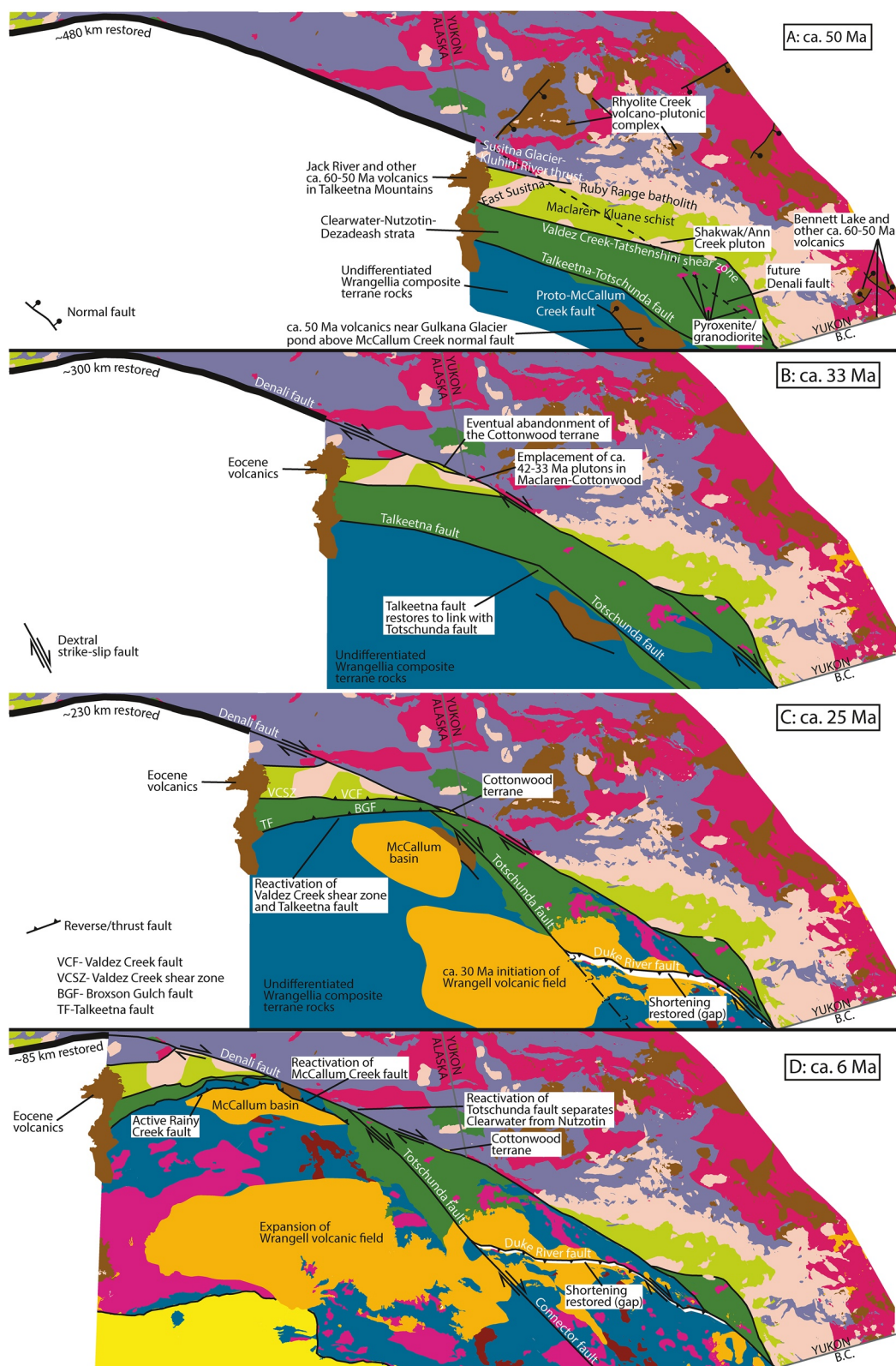


Figure 12.

the eastern-most extent of a suite of plutons emplaced along the Denali fault as far west as Mt. Foraker in the Central Alaska Range (Regan et al., 2020, 2021). Rapid post-emplacement cooling and thermal resetting of the Ar isotopic system in biotite and muscovite only within ~3 km of the plutons (e.g., Benowitz et al., 2014, 2019; Benowitz, Roeske, & Layer, 2011; Waldien et al., 2021) indicate that this phase of the batholith was emplaced at a relatively shallow crustal level.

Ca. 30–20 Ma (Figure 12c): The Oligocene and Early Miocene marks a major change in the geology of southern Alaska and southwestern Yukon, which involves the onset of exhumation in the Alaska Range and the Kluane Ranges (Benowitz et al., 2011, 2012, 2014; Lease et al., 2016; McDermott et al., 2019), drainage reorganization (Benowitz et al., 2019; Brennan & Ridgway, 2015; Finzel et al., 2011, 2015), onset of Wrangell volcanism (Berkelhammer et al., 2019; Brueseke et al., 2019), and development of the St. Elias fold-and-thrust belt (Bruhn et al., 2004; Pavlis et al., 2012). Contemporaneous events in our study area include the post-32 Ma reactivation of the Valdez Creek shear zone indicated by cooling ages and brittle deformation features, development of an imbricate thrust system along the southern flank of the eastern Alaska Range (Valdez Creek, Broxson Gulch, Airstrip, and Rainy Creek faults), and retrograde metamorphism of the Maclaren schist (Waldien et al., 2021). The onset of transpressional deformation in the Denali fault system may have nucleated a short-lived structural complexity (e.g., a restraining bend), which resulted in abandonment of the Cottonwood terrane, a fragment of the Maclaren schist and ca. 33 Ma orthogneiss, on the north side of the active Denali fault strand near the present-day Yukon-Alaska border (Nokleberg & Richter, 2007; Regan et al., 2021; see also Figure 12b). The widespread ca. 30–25 Ma tectonic modification of southern Alaska is generally regarded as an upper plate response to increased plate coupling and progressive flat-slab subduction of the Yakutat oceanic plateau beneath southern Alaska (Enkelmann et al., 2008, 2010; Haynie & Jadamec, 2017; Jadamec et al., 2013).

Late Miocene to Present (Figure 12d): Southern Alaska experienced pulses in bedrock cooling and basin development beginning in the late Miocene. Regional events at this time include uplift and exhumation of the Denali massif (Burkett et al., 2016; Fitzgerald et al., 1993, 1995), exhumation in the western Alaska Range (Benowitz et al., 2012; Haeussler et al., 2008; Lease, 2018), a transition from lacustrine to alluvial facies in basins north and south of the Denali fault (Allen et al., 2016; Ridgway et al., 2002, 2007), development of the Northern Foothills fold and thrust belt (Bemis & Wallace, 2007; Ridgway et al., 2007), reactivation of shortening structures along the southern flank of the Alaska Range (Waldien et al., 2018), expansion of the Wrangell volcanic field (Preece & Hart, 2004), and a regional shift in precipitation related to topographic development (Bill et al., 2018; Otiniano et al., 2020).

One aspect of the late Miocene tectonic event that is integral to the development of the Denali fault system is post-18 Ma dextral slip on the Totschunda fault (Berkelhammer et al., 2019; Milde, 2014). Although it is plausible that the Totschunda fault was part of the proto-Denali fault system before 114 Ma (Trop et al., 2020), the present data only imply linkage with the modern Denali fault since the Late Miocene. Contemporaneous dextral slip on the Totschunda and Denali faults feeds slip from the Totschunda fault onto the Denali fault west of their intersection (Haeussler et al., 2017), which produces transpression west of the junction (Bemis et al., 2015). Due to these observations and the similarity in magnitudes (~80–90 km) of post-7 Ma separation on the Denali fault west of the Denali-Totschunda juncture and post-18 Ma separation

Figure 12. Schematic map-view diagrams illustrating the ca. 50 Ma–Present evolution of the Denali fault system. The diagrams focus on correlative rock units and thus do not account for eroded material. The geology north and east of the Denali fault is not modified from Figure 1 and modern political borders are retained as reference markers. The geology south and west of the Denali fault becomes increasingly schematic further back in time. Eocene volcanic rocks presently in the Talkeetna Mountains (brown map unit south of the Denali fault) may be used to track restoration of the Denali fault. Kinematics are shown only on faults that are active during the time frame. Colors are the same as Figure 1. See text and map annotations for key events in each time frame and Figure 1 for a Present-day time frame. (a) By ca. 50 Ma, all correlative rock packages between the Delta River region and Kluane Lake region had formed. Upon localization, the Denali fault will cut obliquely through the geology (dashed line). (b) By ca. 33 Ma, the Denali fault had begun slipping as a localized dextral fault. The ca. 42–33 Ma intrusions that are shared among the Maclaren and Cottonwood schists are not present in the Kluane schist (see also Figure 8). A structural complexity, probably a restraining step-over, in the Denali fault abandons the Cottonwood schist near the present-day Alaska-Yukon border between 33 and 25 Ma. (c) By ca. 25 Ma, slip on the Valdez Creek fault had nucleated the imbricate thrust system along the south flank of the eastern Alaska Range. Deposition into the McCallum basin records sediment input from uplifted regions of the surrounding Alaska Range (Allen et al., 2016). The Totschunda fault was likely active at this time (Milde, 2014). (d) By ca. 6 Ma dextral slip transfer from the Totschunda fault to the Denali fault was ongoing, which resulted in transpression in the eastern Alaska Range and separation of the Clearwater metasediments from the Nutzotin Mountains sequence. Shortening on the Duke River fault acts to absorb a portion of the plate boundary convergence (Cobbett et al., 2017). The McCallum basin becomes inverted as thrust systems expand the region of elevated Alaska Range topography (Waldien et al., 2018).

on the Totschunda fault, it is likely that both separations accumulated entirely since ca. 7 Ma. Restoring ~85 km of Late Miocene to Present separation on the Totschunda and Denali faults places the Clearwater metasediments adjacent to the Nutzotin Mountains sequence and would also match the Talkeetna fault to the Totschunda fault (see also Figures 11, 12a–12c). Such a restoration is supported both by the rock types near these structures and by crustal tomography revealing nearly identical contrasts in crustal seismic properties across them (Allam et al., 2017). Incorporating the ~85 km of dextral separation on the Totschunda fault is a key component of our palinspastic reconstruction of the Denali fault system because it allows both the ~370 km of separation recorded by correlation of the Dezadeash and Nutzotin strata and the ~465 km of separation recorded by the correlation of the Clearwater metasediments and Dezadeash Formation to be correct.

Transpressional deformation in the Denali fault system during the Neogene was highly partitioned between dextral strike-slip on the Denali fault master strand and Totschunda fault and shortening on thrust systems at the northern and southern flanks of the Alaska Range. The record of long-term cooperation between strike-slip and shortening structures is also reflected in historic seismicity, including the 2002 M_w 7.9 Denali earthquake, which indicates that both strike-slip and shortening structures remain active components of the Denali fault system (Doser, 2004; Eberhart-Phillips et al., 2003; Ratchkovski et al., 2004; Vallage et al., 2014).

5.4. Implications for Strike-Slip Faulting in the North American Cordillera

5.4.1. Separation Versus Slip on the Denali Fault

Cenozoic shortening on structures in the Alaska Range causes the measurements of strike-slip separation to underestimate the magnitude of slip on the Denali fault between the offset markers. Our favored correlation of the ca. 52 Ma Shakwak and Ann Creek plutons yields 465 km of dextral separation. Post-32 Ma reactivation of the Valdez Creek shear zone nucleated the southeast-vergent thrust system that carried the Maclaren schist, Clearwater metasediments, and associated intrusive rocks in the hanging wall (Waldien et al., 2021). Synchronous slip between the thrust system and Denali fault resulted in slip transfer from the Denali fault to the thrusts. As a result of the slip transfer, translation of the Ann Creek pluton relative to the Shakwak pluton took place at a rate lower than the slip rate on the Denali fault. Over time, the accumulated shortening led to a discrepancy in the separation of the offset features relative to the amount of slip on the section of the Denali fault between the correlative plutons. It is not entirely clear how much slip has taken place on the Valdez Creek or Broxson Gulch faults, yet detailed mapping paired with thermochronological and geophysical data sets suggest that these structures accommodated at least 15 km of shortening during the Oligocene and Miocene (Allam et al., 2017; Waldien et al., 2021). Incorporating the Cenozoic shortening into our model of Denali fault evolution reveals that the 465 km of strike-slip separation corresponds to a total slip estimate of ~480 km.

5.4.2. Timing of Strike-Slip Displacement

In agreement with other recent studies (e.g., Murphy, 2018), our review of the ages and separation of features displaced by the Denali fault requires that the ~480 km of displacement on the fault system took place entirely during the Cenozoic. There are two major implications of this outcome.

First, formation and localization of slip on the modern Denali fault appear to have begun as slip on other major strike-slip faults in the Cordillera was decreasing. Both the Border Ranges and Tintina fault systems were active dextral fault systems during the Paleogene, but appear to have experienced minor dextral slip since the Late Eocene (Gabrielse et al., 2006; Little, 1990; Roeske et al., 2003; Ryan et al., 2017; Till et al., 2007). In contrast, we have documented that localization and major slip on the modern Denali fault took place after ca. 52 Ma. This time period corresponds to major changes in the tectonic configuration along the entire margin of western North America, which may be related to changes in the obliquity, rates, and physical properties of incoming oceanic plates (e.g., Atwater, 1989; Doubrovine & Tarduno, 2008; McCrory & Wilson, 2013). The prevalence of Paleogene extensional complexes from British Columbia, Canada into the northern contiguous United States may partially correspond to the coexistence of multiple dextral fault systems that were active at that time (e.g., Andronikos et al., 2003; Foster et al., 2007; Gabrielse et al., 2006). Likewise, the apparent decline of widespread extension in the Late Eocene may record an

increase in localized slip on the Denali fault and a decrease in major slip on neighboring strike-slip fault systems in concert with changing plate boundary conditions.

Second, the recognition of Cenozoic slip on the modern Denali fault allows for larger cumulative margin-parallel displacement of the Wrangellia composite terrane relative to inboard terranes since the Early Cretaceous. Recently published geology-based data sets bear on long-standing hypotheses that the Cordilleran terranes experienced large magnitude ($>1,500$ km) northward transport along dextral fault systems in the mid- and Late Cretaceous (Coutts et al., 2020; Garver & Davidson, 2015; Matthews et al., 2017; Rusmore et al., 2013; Sauer et al., 2019). Our review of slip in the Denali fault system reveals that the oft-cited ~ 370 – 400 km of slip that was inferred to have taken place since the Early Cretaceous is not an accurate assessment of Denali fault slip. We have shown herein that ~ 480 km of slip on the modern Denali fault took place entirely since ca. 52 Ma. Thus, the modern Denali fault should not be grouped with other fault systems contributing to large-scale margin-parallel displacement in the Cretaceous. Rather, thermochronological data and regional geologic correlations suggest the existence of a proto-Denali strike-slip fault system that was likely active during the Early-to-mid-Cretaceous (McDermott et al., 2019; Miller et al., 2002; Wahrhaftig et al., 1975). The amount of displacement and the sense of motion on the proto-Denali fault system are presently not well understood. Finding and interrogating the rock packages that record the slip history of the proto-Denali fault will undoubtedly help reconcile disputes regarding margin-parallel transport of Cordilleran terranes during the Cretaceous. If the proto-Denali fault experienced a phase of dextral slip, northward displacement of the Wrangellia composite terrane along the Denali fault system relative to the North American margin would exceed the ~ 480 km of Cenozoic displacement established herein.

5.4.3. Lithospheric Strength Heterogeneity Following Terrane Accretion

The key feature that allows offset on the modern Denali fault to be determined is the presence of correlative syn-collisional rock packages on both sides of the fault. Thermochronological and thermobarometric data indicate that the Maclaren-Kluane schist and associated batholithic rocks were in the upper ~ 15 km of the crust when the modern Denali fault formed. Because these rock packages, and fabrics within them, were cut obliquely by the fault, it is implied that their mechanical properties did not influence the localization of the fault. Instead, we propose that the mechanical properties of the lower crust and/or lithospheric mantle were more important for controlling the formation and localization of the modern Denali fault. Elements of the post-collisional lower crust and lithospheric mantle in the Cordillera that may have guided localization of the modern Denali fault include a thick mafic root within the Wrangellia composite terrane, differences in mantle hydration as a result of subduction-related magmatism, and/or differences in the thickness of the mantle lithosphere. Such inferences are supported by a variety of geophysical data sets, all of which indicate a fundamental change in the properties of the lower crust and upper mantle across the eastern Denali fault (Allam et al., 2017; Audet et al., 2016; Berg et al., 2020; Miller et al., 2018; O'Driscoll & Miller, 2015; Rasendra et al., 2014; Saltus & Hudson, 2007). The sum of geophysical and geological data from the Denali fault, together with thermochronological and geophysical data sets from other regions of the Cordillera (Enkelmann et al., 2019; Estève et al., 2020), challenge the hypothesis of an active Cordillera-wide weak lower crustal décollement (e.g., Hyndman et al., 2005).

Instead, the contrasting mechanical properties of individual terranes may cause terrane-bounding structures to penetrate the lithosphere. Such a scenario is highly likely for southern Alaska, where the thermal structure of the lithosphere is strongly controlled by the shape of the subducting plate, and lithospheric-scale weaknesses along terrane boundaries (i.e., the Denali fault) are required to accurately model active deformation (Haynie & Jadamec, 2017; Jadamec et al., 2013).

6. Conclusions

Integration of new geologic mapping and geochronology data from the eastern Alaska Range with existing data sets from southwestern Yukon reveals five distinct rock packages that record Cenozoic displacement on the Denali fault: (a) ca. 94–86 Ma Maclaren schist and Kluane schist; (b) the 74–57 Ma phase of the East Susitna batholith and the Ruby Range batholith; (c) ca. 52 Ma granodiorite bodies in the Maclaren schist and the Hayden Lake intrusive suite within the Kluane schist; (d) the ca. 160–144 Ma Clearwater metasediments, Nutzotin Mountains sequence, and Dezadeash Formation strata and ca. 120–100 Ma zoned

pyroxenite-granodiorite bodies that intrude those strata; and (e) Eocene extension-related volcanic rocks and associated shallow intrusions. Restoring these offset features results in ~465 km of dextral separation, and accounting for Neogene shortening in the eastern Alaska Range results in ~480 km of dextral slip in the Denali fault system. All of this slip accumulated since ca. 52 Ma, following the main phase of slip on other major Cordilleran strike-slip faults.

Before offset by the Denali fault system, protolith deposition and prograde metamorphism of the Maclaren-Kluane schist records the closure of a marine basin between the Wrangellia composite terrane and the Cordilleran margin at ca. 95–86 Ma. Underplating and regional metamorphism of the schist took place along east-dipping ductile thrusts (Kluhini River and Valdez Creek-Tatshenshini shear zones) between ca. 82 and 65 Ma. The data presented and summarized herein provide additional evidence for diachronous accretion of the Wrangellia composite terrane along east-dipping structures.

Data Availability Statement

Data presented in this publication are included as supporting information files and have been uploaded to the Geochron database, which is accessible at https://www.geochron.org/dataset/html/geochron_dataset_2020_12_21_7SR8L.

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