Upper-plate Controls on Slab Geometry, Melt Ponding, and Structurally Compelled Localized Alaska Range Suture Zone Arc Magmatism Since ca. 100 Ma

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January 9, 2024

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Abstract

Long-lived magmatic arcs theoretically should migrate large trench perpendicular distances as convergent margin configurations and slab geometry vary over time, however many arc-magmatic belts are spatially localized over 10's of millions of years. We document, by compiling published crystallization geochronology data for southern Alaska (6485 total bedrock and single grain detrital ages combined), that since ca. 100 Ma, arc magmatism has been localized along the Alaska Range suture zone, at times over 500-km inboard. However, since ca. 100 Ma incoming subducting slab characteristics, beneath mobile southern Alaska and convergent margin configurations, varied greatly and include both normal oceanic plate and oceanic plateau subduction, plate vector changes, oroclinal bending and reconfiguration of trench shape, terrane accretion, long distance translation and a Paleocene slab break off/slab window event. Therefore, it is inferred that inherited upper-plate lithospheric shape and heterogeneity must control in part the geometry of the subducting slab below a mobile southern Alaskan margin through hydrodynamic (viscous) mantle wedge "suction" forces. Additionally, crustal thickness heterogeneity may preferentially focus magma ascent through melt ponding along Moho offsets, and upper-plate lithospheric-scale strike-slip faults may be acting as passive and active conduits for arc magmatism. Inherited upper-plate controls on slab geometry could be a factor localizing arc magmatism along other long-lived convergent margin settings.

1 Introduction

The upper-plate location of continental arc magmatism is broadly correlated with the geometry of the subducting slab, with melt generation and individual volcanic centers generally positioned above the subducting slab 100 $\pm$ 40 km depth contours (Isacks and Barazangi et al., 1977; England et al., 2004; Syracuse and Abers, 2006). Numerous factors can influence subducting slab geometry, including the age of the incoming slab (Jarrard, 1986), buoyant topographic highs (e.g., oceanic plateaus: Van Hunen et al., 2002, 2004; aseismic ridges: George et al., 2022), the thickness of the overriding plate (e.g., Sharples et al., 2014), trench shape and curvature (e.g., Chiao et al., 2002), convergence rate (e.g., Billen and Hirth, 2007), and convergence obliquity (e.g., Laurencin et al., 2018). Thus, overall arc localization should be limited, given the dynamic nature of long-lived subduction systems, wherein slabs can break off and active ridges can subduct, the age of the incoming plate can change over time (Grow & Atwater, 1970), incoming plate speed and direction can both vary with time (Stock & Molnar, 1988; Richards & Lithgow-Bertelloni, 1996), and bathymetric highs can be fully subducted (Gutscher et al., 1999) or accreted (Yang et al., 2015). Thus, it is accepted that long-lived arcs should migrate large trench-perpendicular distances as both slab and upper-plate geometries morph over time (e.g. Gianni and Luján, 2021).

Hence, how arcs can be localized on 10^7-year time scales, hundreds of kilometers inboard of a non-stationary trench (Kirsch et al., 2016; Rabiee et al., 2020; Humphreys and Grunder, 2022; Ma et al., 2022), remains an enigma. Furthermore, during periods of slip activity, crustal blocks along strike-slip faults are translated to new positions, intrinsically creating a natural struggle against a clear geological record of arc localization (Alvarado et al., 2016; Trop et al., 2022). Moreover, overriding plates themselves are always in relative motion to the incoming slab (DeMets et al., 2015), and trench-to-arc distance also can vary with time due to accretion (Hughes and Pilatasig, 2002) and subduction erosion (Stern, 2011). Potential arc localization is compounded further by the fact that fluids and hence melt can be generated from a large area of a subducting slab and channeled up-dip (Wilson et al., 2014).

In this work we document arc-localization inboard of the proto and modern Pacific trench along the mobile Alaska Range Suture Zone (*ARZS;* Ridgway et al., 2002*;* Trop et al., 2019) since ca. 100 Ma (Figure 1). Variability of incoming subducting slab characteristics and convergent margin configurations—including both normal oceanic plate and oceanic plateau subduction, plate vector changes, oroclinal bending and reconfiguration of trench shape, terrane accretion, long distance translation (>2000 km; e.g., Stamatakos et al., 2001; Tikoff et al., 2022) and a Paleocene slab break off/slab window event—have not drastically affected *ARSZ* arc location with time. These observations naturally lead to the deduction that a) inherited upper-plate lithospheric thickness and temperature contrasts across the *ARSZ* and northern Alaska (Miller et al., 2018; Gama et al., 2022) and along the western-Northern Cordillera (Clowes et al., 1995; Estève et al., 2020) have played a role in subducting slab geometry under the Wrangell composite terrane of southern Alaska, b) arc localization, since ca. 100 Ma has been in part controlled by inferred upper-plate related hydrodynamic (viscous) mantle wedge “suction” forces, c) upper-plate crustal heterogeneity preferentially focuses magma ascent, perhaps through melt ponding at Moho offsets and d) upper-plate lithospheric-scale strike-slip faults can act as passive and active conduits for arc magmatism (e.g. Regan et al., 2021).

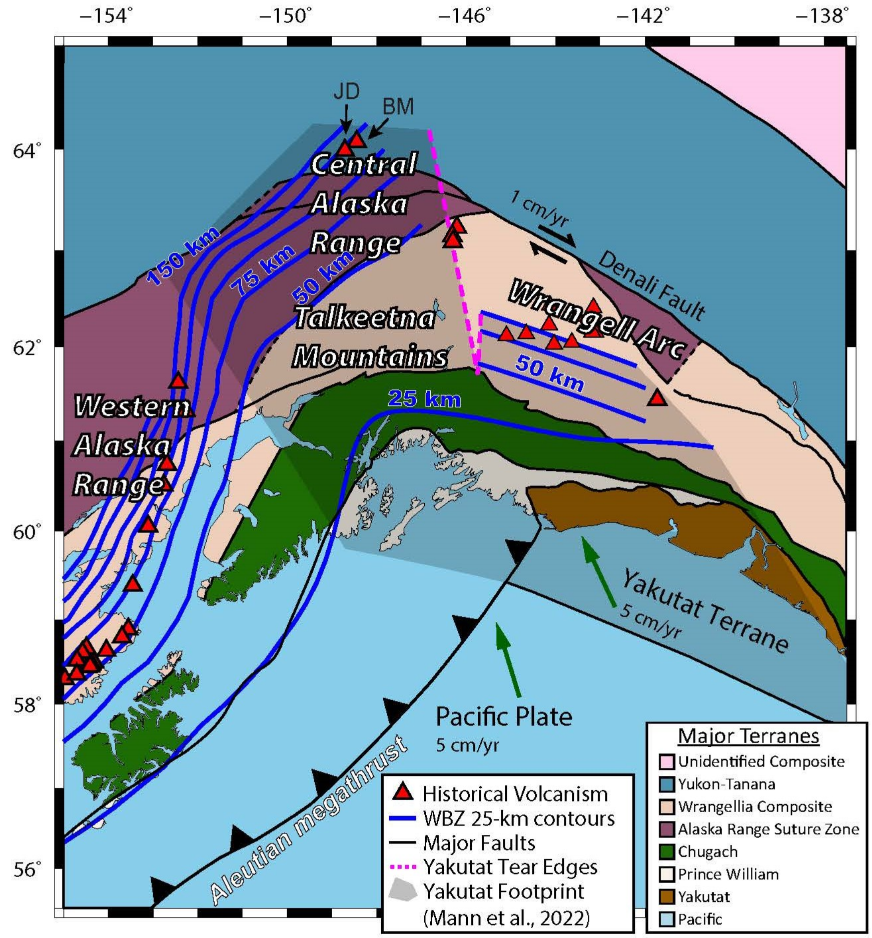

Figure 1. Modern configuration of subducting slab and major terranes across southern Alaska JD–Jumbo Dome, BM–Buzzard Maar. Blue lines are 25-km contours of subducting slab (Mann et al., 2022). Grey polygon is outline of the seismically imaged Yakutat terrane (Mann et al., 2022). Historical volcanos from Cameron (2005). Denali slip rate from Waldien et al. (2021).

2 Geologic Background

2.1 Jurassic to Recent Southern Alaska Convergent Margin Tectonics

Southern Alaska has been a convergent margin since at least the Triassic (Kusky et al., 2007; Trop and Ridgway, 2007), with periods of a) accretionary events (e.g., Jura-Cretaceous: Trop et al., 2020; Eocene: Garver and Davidson, 2015), b) oroclinal bending changing the orientation and shape of the plate margin (e.g. Gillis et al., 2022), c) slab-window/transform tectonics with a gap in arc magmatism (ca. 60-50 Ma; Terhune et al., 2019), d) periods of "normal" subduction (Kula slab–ca. 100-60; Pacific slab–45-30 Ma; Terhune et al., 2019; Trop et al., 2019; Jones et al., 2021; Benowitz et al., 2022) and, e) flat-slab subduction of the Yakutat oceanic plateau with initiation of the associated slab-edge Wrangell Arc (30 Ma to Recent; Ebherhart-Phillips et al., 2006; Worthington et al., 2012; Berkelhammer et al., 2019; Brueseke et al., 2019; Trop et al., 2022).

The accretion of the Wrangellia composite terrane to North American affinity crust to the north-west was the largest addition of crust to the continent in the last 200 million years (Trop and Ridgway, 2007). The generally accepted model is that the Wrangellia composite terrane, primarily oceanic crust, collided along

North America's western coast at around ca. 100 Ma and then was translated >2000 km north along margin-parallel strike-slip fault systems (e.g., Tikoff et al., 2022). The *ARSZ* (Trop et al., 2019) is the suture region between the Wrangellia terrane and rocks of North American affinity to the north (Figure 1). The Denali Fault system delineates the northern boundary of the *ARSZ* (Trop et al., 2019, 2022), and the Talkeetna Fault delineates the southern boundary of the *ARSZ* (Brennan et al., 2011). By ca. 50 Ma the Chugach-Prince William Terrane had been translated and accreted into place south of the Border Ranges Fault system of southern Alaska (Figure 1) (Garver and Davidson, 2015).

Crustal thickness variations exist across the Border Ranges Fault system (Mann et al., 2022), the Talkeetna Fault (Brennan et al., 2011), and the Denali Fault system (Allam et al., 2017) with clear magnetic contrasts across all three structures (Saltus and Hudson, 2022). The Moho offset across the Denali Fault system is ˜10 km (Veenstra et al., 2006; Rossi et al., 2006; Allam et al., 2017; Mann et al., 2022; Yang et al., *this issue*). The Denali Fault also has a well-defined across-strike lithosphere thickness variation: the lithosphere is at least 15 km thicker and is colder to the north of the Denali Fault (>65 km) compared to the south (Miller et al., 2018; Gama et al., 2022). The Arctic Plate north of the Kobuk fault has an even thicker crust (>45 km; Miller et al., 2018; Yang et al., *this issue*) and an apparently cratonic (McClelland et al., 2021) thick (˜200 km) and cold lithosphere (O'Driscoll and Miller, 2015; Jiang et al., 2018; Gama et al., 2022; Pavlis et al.,*this issue*). These crust and lithospheric variations are primarily inherited (i.e. older than ca. 100 Ma) with some post docking shorting along the *ARSZ* (Ridgway et al., 2002) and Eocene extension south of the Hines Creek Fault (Gillis et al., 2022). Notwithstanding these tectonic events, the overall trend of thinner-hotter lithosphere to the south and progressively thicker-colder lithosphere inboard has been long-lived (O'Driscoll and Miller, 2015).

2.2 Mobility of the system and varying age of the subducting slab

The exact location of the paleo-southern Alaska trench is not known, but we assume the trench was near the Border Ranges Fault transform system ca. 95 Ma till ca. 50 Ma (Terhune et al., 2019) and then jumped out closer to its modern position after the accretion of the Chugach-Prince William Terrane (Garver and Davidson, 2015), with additional trench modifications with the arrival of the Yakutat Terrane (e.g., ca. 30 Ma; Brueseke et al., 2019) (Figure 1). Southern Alaska is also bisected by three major dextral strike-slip fault systems. The Tintina Fault has seen ˜490 km of displacement, primarily during the Eocene (Saltus et al., 2007). The Denali Fault system has experienced ˜480 km of displacement since ca. 52 Ma (Waldien et al., 2021). The Border Ranges Fault system has experienced at least ˜700 km of offset between ca. 58 Ma and 50 Ma (Smart et al., 1996). More speculatively the Teslin-Tintina Fault system (not shown) of the Yukon Territory may have experienced 1900 km of displacement since ca. 70 Ma (Johnston et al., 1996). Thus, the location of the *ARZS* has varied with time relative to stable North America. For the Cenozoic, this is clearest for the Central Alaska Range, where this inboard region of the *ARZS* has been translated up to ˜480 km along the Denali Fault system since 52 Ma (Waldien et al., 2021). Furthermore, North America/Alaska was ˜10° degrees further to the north during the late Cretaceous as compared today (e.g., Tikoff et al., 2022) and North America continues to move southwest relative to the Pacific Plate (Anders et al., 1993; DeMets and Dixon, 1999) likely leading to trench encroachment.

Since 84 Ma there have been at least five significant proto-Pacific and Pacific Northeast plate motion changes. Based on Doubrovine and Tarduno (2008), at 84 Ma proto-Pacific and Pacific Northeast slab movement had an orientation of ˜356° NE, then at 67 Ma orientation rotated 14° counterclockwise, th-en at 62 Ma rotated 11° clockwise, and then at 50 Ma rotated 16° clockwise. At 25 Ma there was a 8-15° counterclockwise slab rotation (Jicha et al., 2018) and an 18° clockwise rotation at ca. 6 Ma (Engebretson et al., 1984; Austermann et al., 2011). The rate of convergence has also varied, with rates from 50-200 km/Ma during the last 84 My (Doubrovine and Tarduno, 2008; Elliot et al., 2010). The age and therefore temperature of the subducting slab under Wrangellia has clearly varied through time, but determining the age of ancient subducted slabs is not always determinable as all previous slab material has descended into the mantle. At 50 Ma, the age of the subducting Pacific slab under Alaska was likely young given subduction had reinitiated after the break-off of the Kula plate (e.g., Terhune et al., 2019). The majority of the currently subducting Yakutat slab formed ca. 50 million years ago (Wells et al., 2014).

3 Methods

We compiled bedrock U-Pb zircon and detrital U-Pb zircon watershed populations across southern Alaska and combined them with known plate boundary constraints (subduction vs presence of a slab window) to determine the spatial patterns of arc magmatism since ca. 100 Ma (Figures 2 and 3). We choose this age cut off based on when large segments of the Wrangellia composite terrane would have interacted with the North American plate (e.g. Tikoff et al., 2022), but acknowledge ocean-basin suturing was diachronous in both time and space (Trop et al., 2020; Waldien et al., 2021). We bolstered this dataset with $^{40}Ar/^{39}Ar$ and K-Ar ages on mafic dikes and volcanics and detrital $^{40}Ar/^{39}Ar$ lithic grains. We did not compile $^{40}Ar/^{39}Ar$ and K-Ar ages on hornblende, muscovite, biotite, or potassium feldspar to avoid dates that reflect exhumation or metamorphic related events—not true magmatic events except from magmatic products from the Wrangell Arc. We generally avoided ashfall samples, but some thick welded tuffs are included in the dataset. The detrital datasets may include some recycled grains from sedimentary or metamorphic lithologies (Wilson et al., 2015), but the detrital datasets mimic the igneous bedrock datasets, except for the Wrangell Arc. We do not include detrital ages from Cretaceous-Cenozoic strata to avoid potentially far-traveled sources (Finzel et al., 2019).

Locations were all plotted and assumed to be in the geodetic datum, WGS84. For the purposes of this study the potential 500- to 1000-meter difference from NAD27 is not germane, but we recommend attempting to figuring out (often not reported) the original datum applied, if using this compiled database for other purposes. Detrital geochronology datasets for individual watersheds from the Western and Central Alaska Range Arc and the Wrangell Arc are presented individually in the supplement, but compiled for figure presentation. The watershed outlines are presented in the references noted in the supplemental files. Data and further references are available in supplemental tables S1, S2, S3, and S4.

We overlayed our geochronology dataset on a digital elevation model and a simplified terrane map of Alaska (Figures 4 and 5). To highlight arc localization, time slices were created for 100-60 Ma, 60-50 Ma, 50-30 Ma, and 30 Ma to Recent for the western and Central Alaska Range Arcs (northern continental Aleutian since ca. 48 Ma; Bezard et al., 2021) and the Talkeetna Mountains. For the Western and Central Alaska Range Arcs, time slices are 100-60 Ma, 60-50 Ma, 50-25 Ma, and 25 Ma to Recent to reflect the continuation of arc magmatism after the initnal arrival of the Yakutat slab at ca. 30 Ma (Brueseke et al., 2019). These divisions are based on known periods of arc magmatism, pulses of arc magmatism, and significant changes in plate boundary conditions (Herriott et al., 2014; Lease et al., 2016; Finzel et al., 2019; Trop et al., 2019; Terhune et al., 2019; Fasulo et al., 2021; Jones et al., 2021, Regan et al., 2021, 2022; Benowitz et al., 2022, Trop et al., 2022). We also compare bedrock and detrital data with a map of crustal thickness variations (Figure 6) (Yang et al., *this issue*).

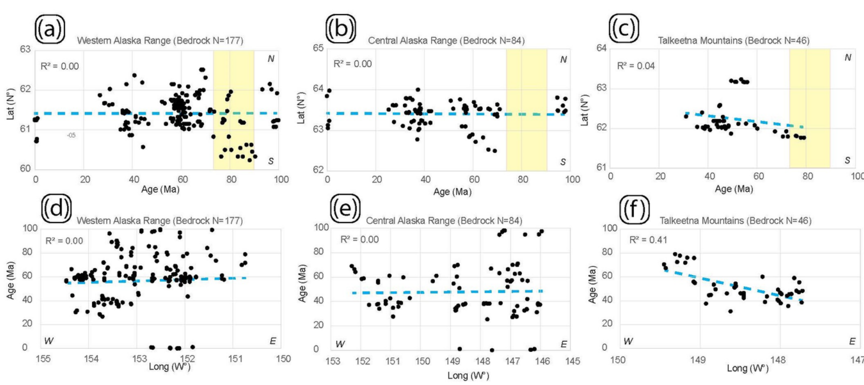

Figure 2. Latitude vs Age and Longitude vs Age for bedrock samples <100 ca. Ma from the Western (a,

d)) and Central Alaska Range Arc (b,e) and the Talkeetna Mountains (c,f). Wrangell Arc not show because of a complicated history involving slab edge droop and dissection by the Totschunda Fault. See the text and Trop et al., 2022 for a detailed reconstruction of the Wrangell Arc spatial variation. Yellow swath highlights the shift in magmatism ca, 87 Ma to 75 Ma to south for the Western Alaska Range and the Talkeetna Mountains and the gap in magmatism in the Central Alaska Range. S:south; N: north; E:east; W: west. Data in tables S1, S2, S3, and S4.

4 Results

4.1 Western Alaska Range Arc

We compiled 179 bedrock ages and 422 single grain U-Pb zircon ages from the Western Alaska Range Arc (Figures 2, 3, 4, 5, 6, 7; references in supplemental S1). The swath of arc magmatism along the Western Alaska Range Arc proceeds from ca. 100 Ma to 25 Ma with re-initiation of the arc since ca. 1 Ma, based on the compilation of both bedrock and detrital geochronology datasets (Herriott et al., 2014; Lease et al., 2016; Jones et al., 2021; Cameron et al., 2022). Periods of peak magmatism are ca. 98 Ma, 60 Ma, throughout the Oligocene and since ca. 1 Ma (Figure 3). There are no substantial East-West or North-South trends with time besides a) a jump trenchward in magmatism from ˜87 Ma to ˜75 Ma and b) the modern Denali magmatic gap (Rondenay et al., 2010) between Hayes Volcano and Jumbo Dome-Buzzard Maar to the northeast (Figures 1 and 2).

4.2 Central Alaska Range Arc

We compiled 83 bedrock ages and 1325 single grain U-Pb zircon ages from the Central Alaska Range Arc (Figures 2, 3, 4, 5, 6, 7; references in supplemental S2). The swath of arc magmatism along the *ARSZ* pulses from ca. 100 Ma to 25 Ma, with re-initiation of the arc since ca. 1 Ma based on the compilation of both bedrock and detrital geochronology datasets (Athey et al., 2006; Andronikov et al., 2010; Lease et al., 2016; Regan et al., 2020; 2021; Fasulo and Ridgway, 2021; Benowitz et al., 2022; Brueseke et al., 2023) with a focus along the Denali Fault system. Overall, there is minimal magmatism north of the Denali Fault system with Jumbo Dome (Cameron et al., 2015) and Buzzard Maar (Andronikov et al., 2010) being historical volcanos ˜575 km from the modern trench (Fig. 1). Similar to the Western Alaska Range Arc, periods of peak magmatism are ca. 95 Ma, ca. 60 Ma, and ca. 40 Ma (Figure 3). There are no substantial East-West or North-South trends with time except a gap in magmatism from ˜87 Ma to ˜75 Ma when it shifted outboard to the Talkeetna Mountains and the southern Western Alaska Range (Figure 2).

4.3 Talkeetna Mountains

We compiled 86 bedrock ages and 2817 single grain U-Pb zircon ages from the Talkeetna Mountains (Figures 2, 3, 4, 5, 6, 7; references in supplemental S3). The Talkeetna Mountains have periods of peak magmatism of ca. 80 Ma, ca. 58 Ma, and ca. 45 Ma (Figure 3) (e.g., Terhune et al., 2019; Finzel et al., 2019). This area is mostly south of the*ARSZ,* but is shown for completeness. The ca. 80 Ma magmatic peak occurs during a period when magmatism ceases in the Central Alaska Range Arc (ca. 87 Ma to 75 Ma) (Figure 2). The ca. 58 Ma and ca. 45 Ma magmatic peaks in the Talkeetna mountains reflect the slab window and relict slab window magmatism (Cole et al., 2006; Cole et al., 2007).

4.4 Wrangel Arc

We compiled 246 bedrock ages and 4347 single grain ages (U-Pb zircon zircon and $^{40}Ar/^{39}Ar$ lithic grain ages) from the Wrangell Arc (Figures 3, 4, 5, 6, 7; references in supplemental S4). The swath of Wrangell Arc magmatism along the*ARSZ* proceeds from ca. 100 Ma to Recent based on the compilation of both bedrock and detrital geochronology datasets (Richter et al., 1990; Berklehammer et al., 2019; Brueseke et al., 2019; Trop et al., 2022). The detrital dataset is more diverse than the bedrock dataset, which may reflect detrital grains being sourced from metamorphic and sedimentary sources, or more likely reflects preferential bedrock sampling of Wrangell aged lavas. Wrangell Arc periods of peak magmatism are ca. 60 Ma and ca. 30 Ma to Recent (Figure 3). Wrangell Arc magmatism occurs south of the Denali Fault for the entirety of its existence, but shifts slightly with time generally from north (ca. 30 Ma to 18 Ma) to east (ca. 18 Ma to

13 Ma), to west (ca. 13 Ma to 16 Ma), and finally to a distinct northwest trend 6 Ma to 1 Ma slightly (see Trop et al., 2022). From 30 Ma to 6 Ma magmatism is also focused along the Totschunda and Duke River Faults with limited magmatism along the Totschunda Fault 6 Ma to Recent (Trop et al., 2022).

4.5 Compiled Alaska suture zone magmatic history

The combined datasets show peak periods of magmatism along the*ARSZ* at ca. 95 Ma, ca. 60 Ma, ca. 40 Ma and Recent (Figure 3). The Wrangell Arc area has a slightly different history, reflecting the shutting off of the western and eastern Alaska Range Arcs at ca. 25 Ma (Trop et al., 2019; Jones et al., 2021; Benowitz et al., 2022) and the initiation of the Wrangell Arc at ca. 30 Ma (Trop et al., 2022).

4.6 Geophysics Compilation

The Western Alaska Range Arc generally follows the *ARSZ* which has an east-west crustal thickness step (Figure 6) (Gama et al., 2022) and a strong magnetic signature gradient (Saltus and Hudson, 2022). The Central Alaska Range Arc is located primarily south of the Hines Creek Fault and borders both sides of the Denali Fault system in the*ARSZ* (Figure 5). There is a crustal thickness step across both the Denali (Allam et al., 2017) and Hines Creek Faults (Brennan et al., 2011, Allam et al., 2017) (Figure 6), and a strong magnetic signature break across the Talkeetna Fault (Saltus and Hudson, 2022). The Wrangell Arc is located in the *ARSZ* where there also is a crustal thickness step (Figure 6) (Allam et al., 2017) and a magnetic signature break (Saltus and Hudson, 2022).

The modern Yakutat slab has a shallow dip of ˜5° for nearly 200-km inboard of the trench and is in direct contact with the overriding crust until it reaches the Chugach-Prince William Terrane-Wrangellia Terrane boundary (Kim et al., 2014; Mann et al., 2022). Once the subducting slab reaches roughly the Talkeetna Fault, its dip increases to ˜20° (Ferris et al., 2003; Rondenay et al., 2010); near the Denali fault it begins steeply dipping into the mantle (Jiang et al., 2018; Yang et al., *this issue*). The overriding plate crust has a northward-thickening wedge shape from roughly 10 to 40 km thick under the Chugach-Prince William terrane, and is at 35-55 km under the Wrangellia composite Terrane, 35-40 km under the *ARZS* , 25 km under the Yukon Tanana Terrane, 35-40 km thick north of the Tintina Fault and almost 50-km thick north of the Kobuk Fault under the Arctic Plate (Veenstra et al., 2006; Rossi et al., 2006; Brennan et al., 2011, Miller et al., 2018; Mann et al., 2022; Gama et al., 2022; Yang et al., *this issue*). There are Moho offsets across each of these tectono-boundaries The upper-plate lithosphere is absent or extends to ˜50-km depth beneath the Chugach-Prince William terrane, Wrangellia composite terrane, and*ARZS* ; is 65-125 km thick beneath the Yukon Tanana terrane, 125-145 km thick beneath the region the north of the Tintina fault, and up to 200-km thick north of the Kobuk Fault under the Arctic Plate (O'Driscoll and Miller, 2015; Miller et al., 2018; Jiang et al. 2018; Gama et al., 2022).

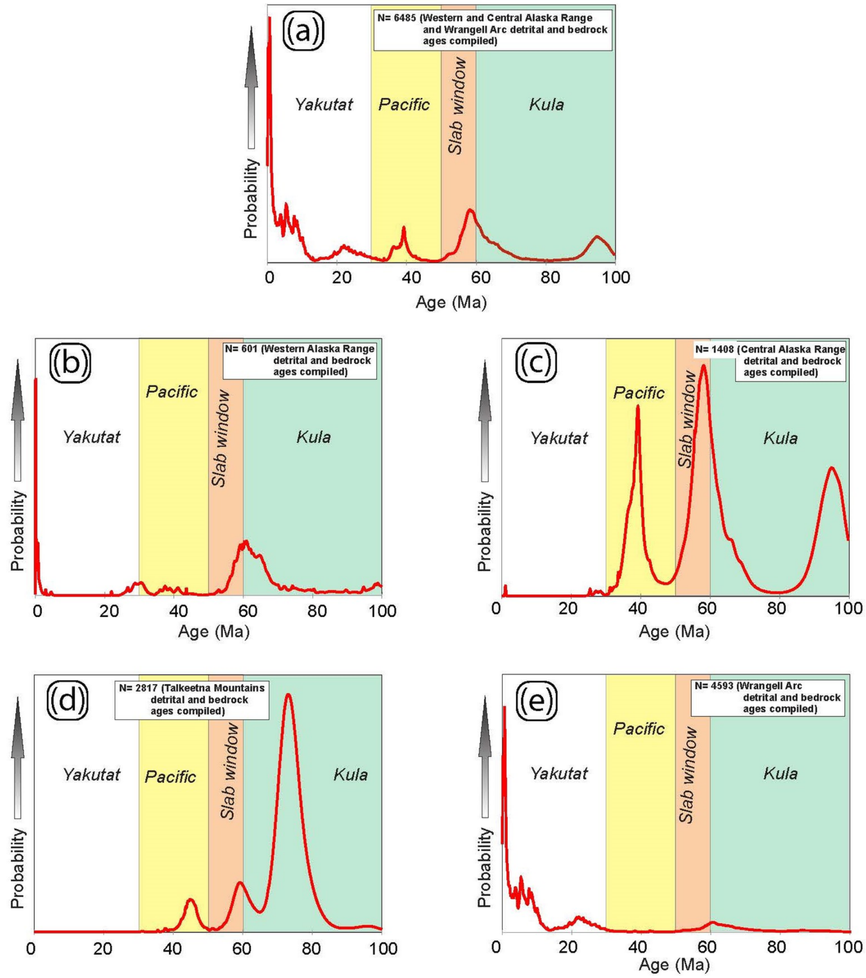

Figure 3. Probability Density plot of compiled published bedrock ages and detrital single grain ages <ca. 100 Ma from the a) the Western Alaska Range, Central Alaska Range, and the Wrangell Arc combined (*ARZS* arcs), b) Western Alaska Range, c) the Central Alaska Range, d) the Talkeetna Mountains, and e) the Wrangell Arc. Data in tables S1, S2, S3, and S4. Kula slab subduction period (100-60 Ma); slab window (60-50 Ma); Pacific slab dominated (50-30 Ma); and Yakutat slab dominated (30 Ma to Recent). Note the Western and Central Alaska Range Arcs have continued magmatism to ca. 25 Ma before a Yakutat slab related cessation in magmatism till arc reinitiation ca. 1 Ma (Trop et al., 2019; Jones et al., 2021; Brueseke et al., 2023).

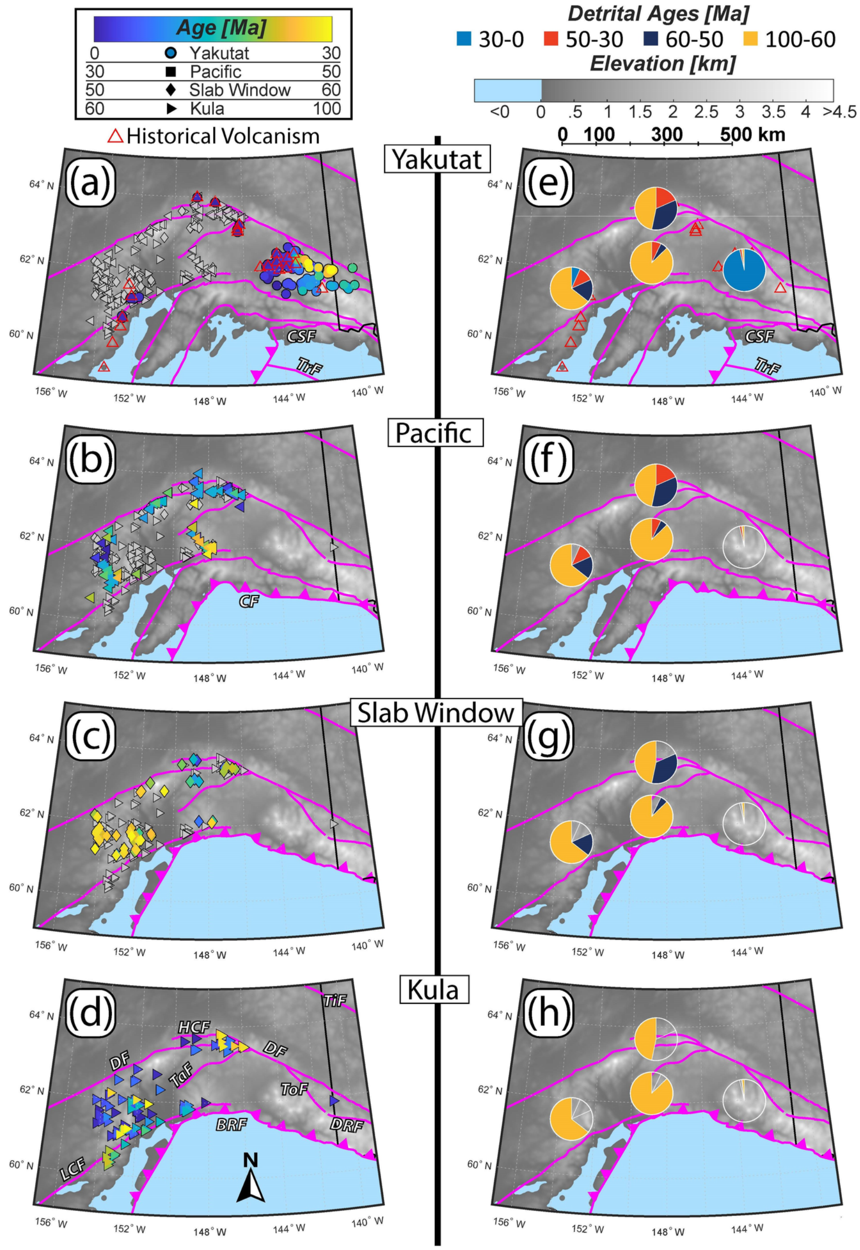

Figure 4. Compilations of magmatic ages in four main time periods. The trench is moved to the position of each time period's outboard terrane. Within each time period, data points are plotted with color representing age, at the sampled location. Samples with ages from previous periods are in gray. (a-d) Bedrock ages. (e-h) Detrital ages. (a)&(e) Modern Yakutat slab dominated configuration (30-0 Ma). (b)&(f) Pacific dominated subduction configuration (50-30 Ma). (c)&(g) Slab window configuration, after Kula plate breakoff (60-50 Ma). (d)&(h) Kula subduction configuration (100-60 Ma). TiF–Tintina Fault, DF–Denali Fault, HCF–Hines Creek Fault, TaF–Talkeetna Fault, LCF–Lake Clark Fault, ToF–Totschunda Fault, DRF–Duke River Fault, BRF–Border Ranges Fault, CF–Contact Fault, CSF–Chugach-St. Elias Fault, TrF–Transition Fault. Data available in tables S1, S2, S3 and S4. For the Western and Central Alaska Range Arcs the 50-30 Ma divison is 50-25 Ma because magmatism continues for 5 Ma after the arrival of the Yakutat slab.

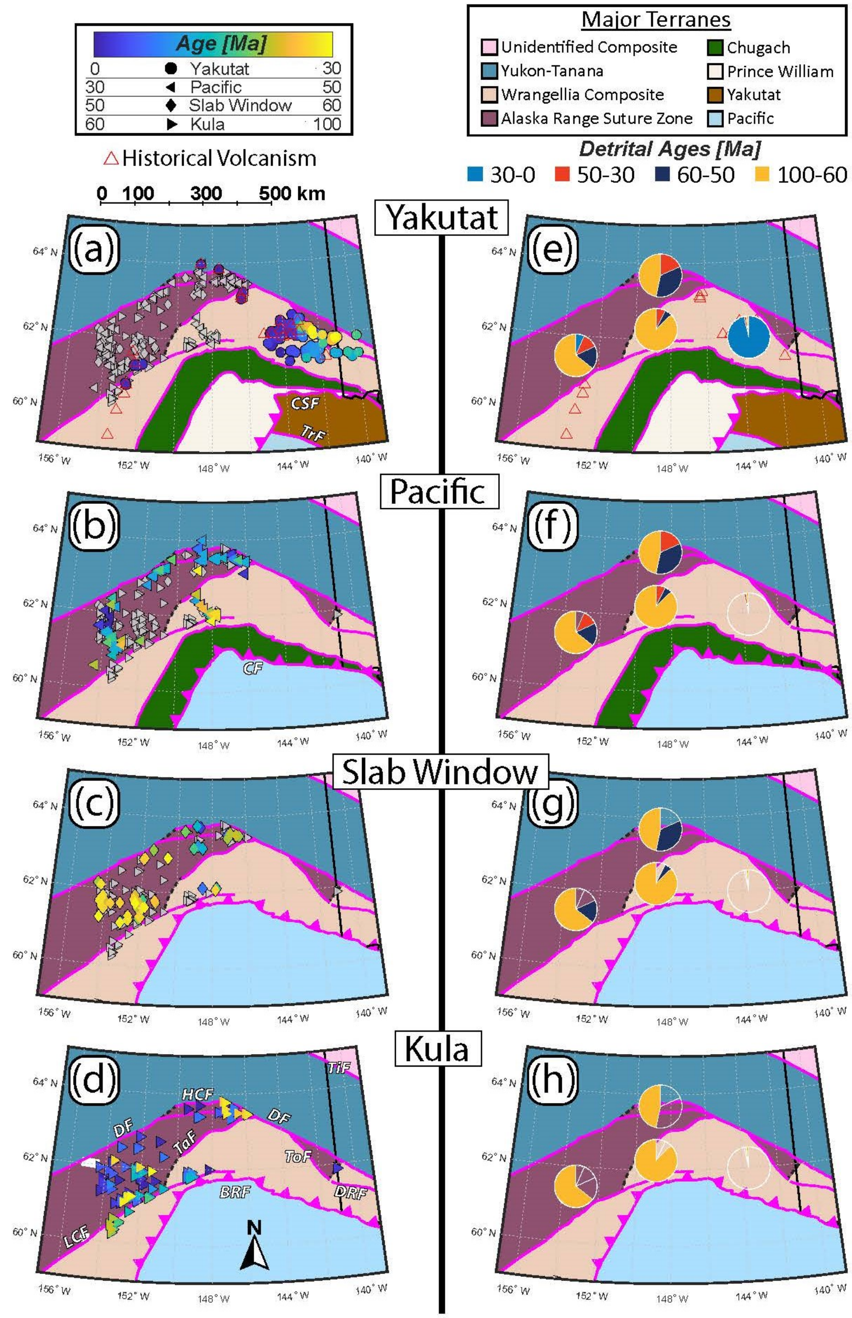

Figure 5. Compilations of ages in four main time periods. Map backgrounds are major regional terran. (a-d) Bedrock ages. (e-h) Detrital ages. (a)&(e) Modern configuration (30-0 Ma). (b)&(f) Pacific subduction configuration (50-30 Ma). (c)&(g) Slab window configuration, after Kula plate breakoff (60-50 Ma). (d)&(h) Kula subduction configuration (100-60 Ma). All labels as in Fig. 4.

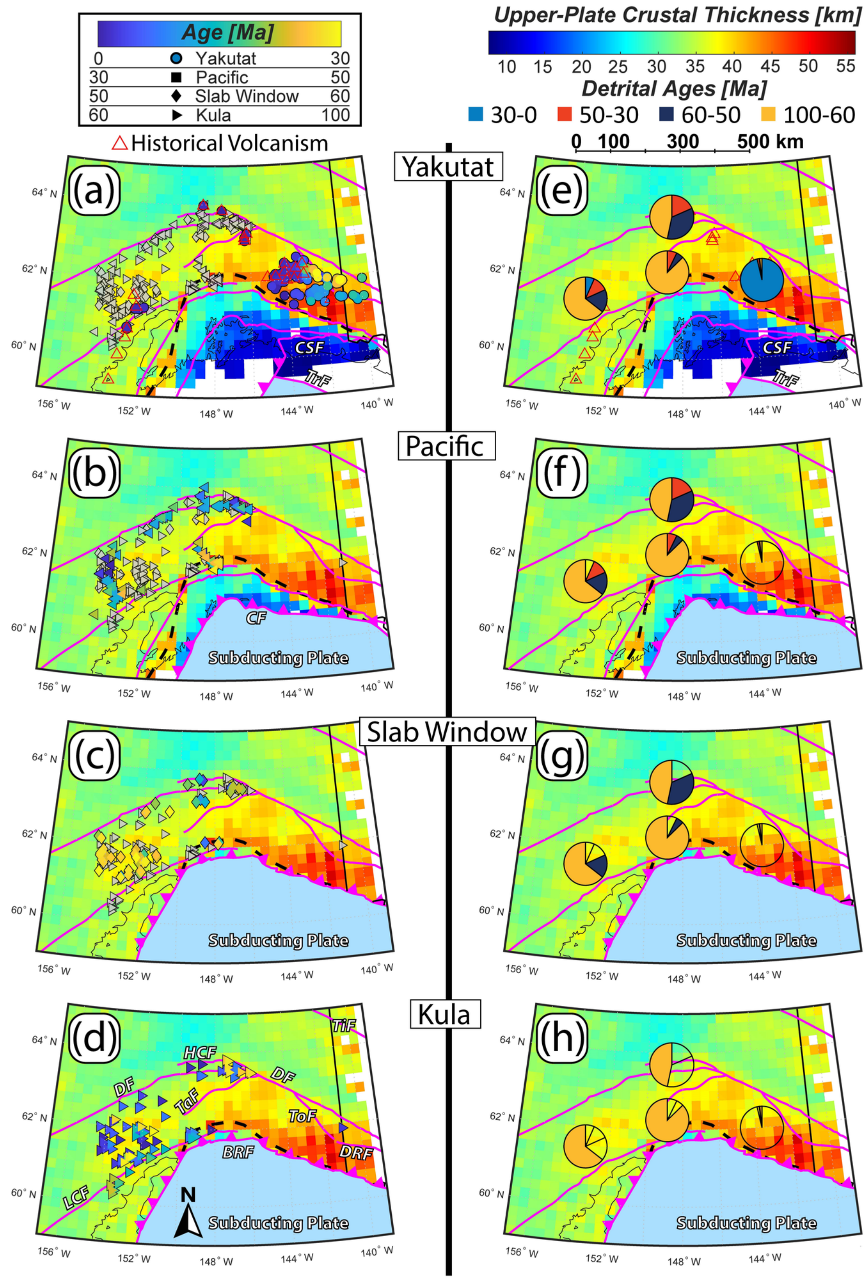

Figure 6. Compilations of ages in four main time periods. Map background is crustal thickness average from synthesis work published in this monograph (Yang et al., *this issue*). (a-d) Bedrock ages. (e-h) Detrital ages. (a)&(e) Modern configuration (30-0 Ma). (b)&(f) Pacific subduction configuration (50-30 Ma). (c)&(g) Slab window configuration, after Kula plate breakoff (60-50 Ma). (d)&(h) Kula subduction configuration (100-60 Ma). All labels as in Fig. 4.

5 Discussion

5.1 Arc localization in the Alaska Range Suture Zone since ca. 100 Ma

Based on the mapped compilation (N= 6485 ages total) of detrital single grain and bedrock sample ages, arc magmatism has been localized along the *ARZS* since ca. 100 Ma (Figures 1, 4, 5, 6, and 7). This arc localization 1) occurred as far as ˜300 and 550 km from a subduction interface that generally moved oceanward with time through accretion (Garver and Davidson et al., 2015; Trop et al., 2019), 2) occurred in segments of the upper-plate that were mobile along regional lithospheric and crustal-scale strike-slip faults (Allam et al., 2017; Waldien et al., 2021; Gama et al., 2022), 3) involved slabs of different ages (Engebretson et al., 1984; Wells et al., 2014), variable convergence angles and velocities (Sharp and Clague, 2006; Doubrovine and Tarduno, 2008; Jicha et al., 2018), and involved slabs of varying thicknesses (Worthington et al., 2012; Mann et al., 2022), 4) was maintained after oroclinal bending which greatly modified the margin geometry (e.g., Gillis et al., 2022) and slab break off resulting in a slab window event (Terhune et al., 2019), and 5) mostly occurred south of the Denali Fault system (including the Hines Creek segment) along the*ARZS* from ca. 100 Ma to Recent.

By deduction, pre-existing features of the Alaska upper-plate must be playing a first-order role in localizing magmatism. Sutures can act as passive conduits for magma (Richard, 2003) and play an active role in magmatism localization (Gómez-Vasconcelos et al., 2022). However, melt generally rises vertically (Hall and Kincaid, 2001) and slabs subducting under the *ARSZ* must have maintained a depth roughly around 100 ± 40 km (Isacks and Barazangi et al., 1977; England et al., 2004; Syracuse & Abers, 2006) since 100 Ma to generate melt in the general vicinity of the *ARSZ* . Furthermore, there is no dominant structure along the spine of the Western Alaska Range Arc to facilitate arc magmatism localization (Figure 1).

5.2 Mechanisms for Arc localization in the *ARSZ* since ca. 100 Ma

The overriding plate in a subduction zone influences the geometry of the subducting slab through its effect on the mantle flow field: flow around the subducting slab can cause both low dynamic pressures above the slab and high dynamic pressures below, and lead to forces that counteract negative slab buoyancy and decrease subducting dip angle (Stevenson & Turner, 1977; Tovish et al., 1978; Rodríguez-Gonzalez et al., 2012; Liu, 2022). It has also been demonstrated through geodynamic modeling and natural examples that the presence of a region of thicker-colder upper-plate moving toward the trench can lead to increased mantle-flow-related hydrodynamic "suction" in the mantle wedge (van Hunen et al., 2004; Manea and Gurnis, 2007; Rodriguez-Gonzalez et al., 2012). Thus, slab dips beneath continents are generally shallower by ˜20deg than under oceanic lithosphere and flat-slab subduction under oceanic lithosphere has not been documented (Jarrard, 1986; England et al., 2004; Syracuse and Abers, 2006).

At ca. 80 Ma the the Wrangellia composite terrane of Alaska was at a paleo-latitude of 53deg +- 8degN (Stamatakos et al., 2001) and by ca. 50 Ma the terrane was at or near modern latitudes (Panuska et al., 1990). More speculatively, at ca. 100 Ma the Wrangellia composite terrane of Alaska may have been located off the coast of the western United States (e.g., Tikoff et al., 2022). The incoming slab as well as the upper-plate characteristics varied along the >2000 km northward translation of the Wrangellia composite terrane. Regardless of the exact paleo-latitude position, the Wrangellia composite terrane would have been outboard of a plate with a thicker (>100 km) lithosphere (Porter and Reid, 2021) when translated north along the modern day Western United States (Figure 7a). At ca, 80, when the Wrangellia composite terrane was being translated along the coast of modern-day British Columbia the inboard lithosphere would have been relatively thin (˜80-100 km thick) (Clowes et al., 1995). Interestingly, this is the time when arc magmatism ceased in the Central Alaska Range and shifted outboard to the Western Alaska Range and Talkeetna Mountains, which suggests slab steepening or rollback during this time period or possibly the translation of the Wrangellia composite terrane over a steeper dipping slab segment. The trench distance to thick-cold craton for the Wrangellia composite terrane would have been ˜350 km from the >150 km thick Mackenzie craton when passing by the modern-day Yukon Territory around ca. 75 Ma when arc magmatism reinitiated in the Central Alaska Range (Schaeffer and Lebedev, 2014; Esteve, 2020 Esteve et al., 2020).

The period of ca. 60 Ma to 50 Ma was a dynamic period in Alaska history with the Kula plate breaking off, the creation of a slab window under southern Alaska, the final translation of the Chugach-Prince William Terrane into place, and syn-tectonic oroclinal bending (Figure 7b) (Garver and Davidson 2015; Terhune et al., 2019; Gillis et al., 2022). The shape of trench was modified at this time, as was any pre-existing subduction channel. However, when subduction reinitiated at ca. 48 Ma (Bezard et al., 2021; Jones et al., 2021; Benowitz et al., 2022) the continental arc once again returned to the *ARSZ* .

The lithosphere north of the Denali Fault system is of Laurentian (Dusel-Bacon et al., 2013, 2017; Jones et al., 2017) and Caledonian affinity (McClelland et al., 2021), where the terranes of southern Alaska are primarily of oceanic affinity (e.g., Trop and Ridgway et al., 2007). This contrast is clear in both the lithosphere being thicker and colder north and west of the *ARSZ* (Gama et al., 2022). Additionally, the lithosphere beneath northern Alaska is even thicker (150-200 km) and colder (Figure 7c) (O'Driscoll and Miller, 2015; Jiang et al., 2018; Gama et al., 2022). Alaska/North America has been moving to the southwest since the late Cretaceous (e.g. Tikoff et al., 2022) leading to an overall trenchward motion of interior Alaska which continues today (McConeghy et al., 2022). Hence, we prefer a geodynamic model where the upper-plate lithospheric shape and dynamics induce hydrodynamic "suction" forces that have controlled the geometry of the underlying Alaska slab since ca. 100 Ma. The ca. 30 Ma to Recent "flat" slab subduction of the Yakutat oceanic plateau beneath Alaska also likely reflects a component of upper plate hydrodynamic "suction" (Figure 7d). Many studies have demonstrated that anomalously thick/buoyant oceanic slabs alone do not lead to shallow subduction, but also need a component of mantle-wedge suction (O'Driscoll et al., 2009; Manea et al., 2012; Skinner and Clayton, 2013).

Additional features of the upper plate are also likely contributing to arc localization in the *ARSZ*. Sutures zones, which are regions of crustal weakness (Sykes, 1978) can act as pathways that focus rising melt (Dahm et al., 2020). It has also been suggested that upper-plate faults which penetrate all the way through the crust can funnel slab related melts into the upper crust (Marot et al., 2014), and it has been documented that extensional kinematic environs along strike-slip faults can lead to magmatism localization (Tibaldi et al., 2009; Mathieu et al., 2011; Gomez-Vasconcelos et al., 2020; Webb et al., 2020). The Hines Creek, Denali and Totschunda Faults bounding the northern *ARSZ* are Cretaceous and still active (Miller et al., 2002; Benowitz et al., 2014, 2022; Trop et al., 2020), lithospheric-scale (Eberhart-Phillips et al., 2003; Allam et al., 2017; Gama et al., 2022) strike-slip faults (Figure 7). Eocene-dissected plutons (Regan et al., 2021), fault zone Cretaceous-Oligocene-Miocene dike swarms (Brueseke et al., 2019; Trop et al., 2019, 2020) and Cretaceous-to-Recent magmatism focused along the Denali and Totschunda Faults (Benowitz et al., 2022; Trop et al., 2022) support these structures having an active role in arc magmatism localization.

Another scenario leading to arc localization along the *ARSZ* since ca. 100 Ma is possible melt ponding along Totschunda and Denali Fault Moho depth offsets (Figure 7). Melt ponding has been inferred below upper-plate structures from seismic imaging (e.g., MacKenzie et al., 2010; Rondenay et al., 2010). We speculate that Moho depth offsets, such as those across the Totschunda and Denali Fault systems (e.g., Gama et al., 2022), may be acting as catchments for melt rising through the convecting mantle wedge and hence contribute to focusing magmatism along crustal-scale structures.

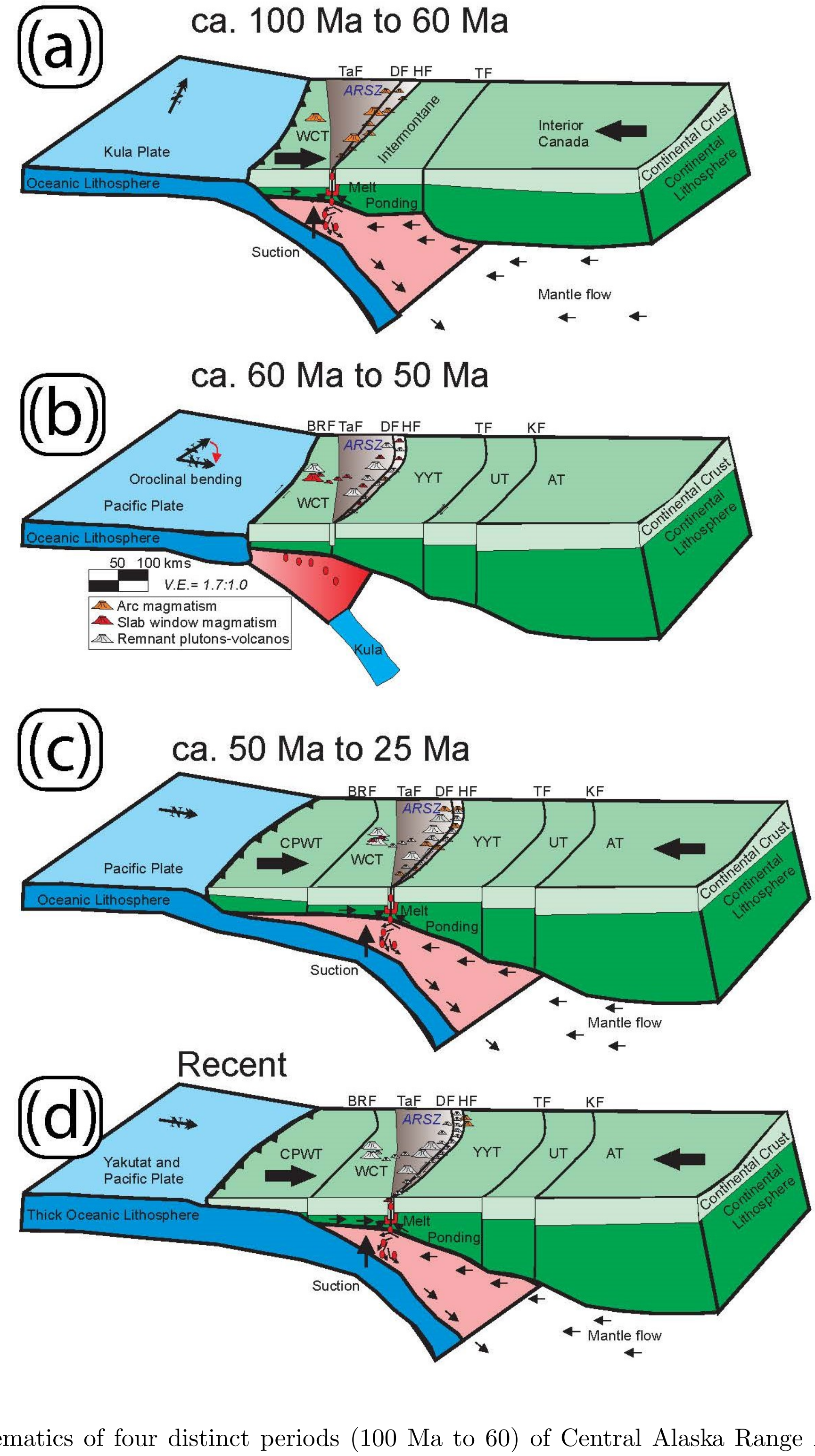

Figure 7. Schematics of four distinct periods (100 Ma to 60) of Central Alaska Range Arc magmatism. Translation along the Tintina and Denali Faults not shown nor is rotations of the incoming slab during plate vector changes discussed in the text. Mantle flow into the mantle wedge, enhanced by trench advancement of the thick-cold lithosphere of interior Western USA/Western Canada and the Arctic Plate (> 150 kms;

O'Driscoll and Miller 2015; Tikoff et al., 2022) likely leads to lower pressure and upper plate suction (e.g. Manea et al., 2012). a) After the mid-Cretaceous docking of the Wrangellia Composite Terrane off the coast of the Western USA/Western Canada (e.g. Trop et al., 2020; Tikoff et al., 2022) there was a long period of "normal" subduction from ca. 100 Ma to 60 Ma with arc magmatism focused in the *ARZS* with minor magmatism north of the Border Ranges Fault (Bleick et al., 2012). During this time period the *ARZS* underwent shorting (e.g. Trop et al., 2019). There was a short period of steeper slab subduction when the arc moved outboard towards the trench between ca.87 Ma and 75 Ma (Figure 1) that is not given its own schematic. b) The Alaska convergent margin was likely a transform system from ca. 60 Ma to 50 Ma after break off of the Kula slab (Terhune et al., 2019). During this time period 44° ± 11° counter-clock wise oroclinal bending was occurring (Coe et al., 1989; Gillis et al., 2022) and slab window magmatism in the*ARZS* and to the south along the hinge of the orocline (Cole et al., 2006; e.g. Terhune et al., 2019). This time period was also the timing of rapid slip along the Border Ranges Fault (Smart et al., 1996) and the Tintina Faults (Saltus et al., 2007). c) After accretion of the Chugach-Prince William Terrane (Garver and Davidson, 2015) and a Pacific plate motion change at ca. 50 Ma (Sharp and Clague, 2006) subduction reinitiated and the trench jumped outboard about ˜200 km. This time period was the start of rapid slip along the Denali Fault system (Waldien et al., 2021). There was minor post-slab window magmatism north of the Border Ranges Fault (e.g. Terhune et al., 2019) with magmatism once again focused in the *ARZS.* At ca. 30 Ma the Yakutat oceanic plateau (Worthington et al., 2012) started to subduct under Alaska (Brueseke et al., 2019), but magmatism continued in the*ARZS* till ca. 25 Ma (Trop et al., 2019). d) The shallow subduction of the Yakutat oceanic plateau continued till ca. 1 Ma when collision and slab segmentation initiated (Brueseke et al., 2023). This slab segmentation led to the rejuvenation of the central Alaska Range arc. Crustal thickness variations compiled from Veenstra et al. (2006), Brennan (2011), Miller et al. (2018), and Mann et al., 2021. Lithosphere thickness variations compiled from O'Driscoll and Miller (2015), Jiang et al. (2018) and Gamma et al. (2022). Recent mantle flow and surface velocity directions from McConeghy et al. (2022) and are inferred to be similar during past subduction regimes. AT: Arctic Plate; UT: Unidentified Terranes; YTT: Yukon Tanana Terrane; ARZS: Alaska Range Suture Zone; WCT: Wrangellia Composite Terrane; CPWT: Chugach-Prince William Terrane; KF: Kobuk Fault; TF: Tintina Fault; HF: Hines Creek Fault; DF: Denali Fault; TaF: Talkeetna Fault; BRF: Border Ranges Fault. Scale bar approximate. North Arrow rotates with paleo-location of the Wrangell composite terrane (e.g. Terhune et al., 2019; e.g. Tikoff et al., 2022).

5.3 Other examples of long-lived arc localization

Globally, there are many past and present examples of localized arc magmatism. The Gangdese arc of southern Tibet was broadly localized ca. 100 Ma to 45 Ma (Ma et al., 2022). Magmatism has been localized and focused along an inherited lithospheric-scale boundary in Iran from Eocene to late Miocene times (Rabiee et al., 2020). Magmatism was localized along the Burma plate during Cretaceous and Eo-Oligocene arc magmatic events while the plate was being translated >2000 km and undergoing different subduction orientations/slab configurations (Westerweel et al., 2019; Licht et al., 2020).

The Cascade Arc has been emplaced along the same general region of crust since ca. 45 Ma (Humphreys and Grunder, 2022), with Eocene, Oligocene, Miocene, Pliocene, and Pleistocene magmatic products intruded next to and through one another. Even classic examples of long-lived arcs such as the northern Andes (Ducea et al., 2015) appear to be emplaced along pre-existing suture zones. About 70 million years of arc magmatism in South America has generally been emplaced along the Peletec suture zone in Ecuador with no Cenozoic arc magmatic products emplaced to the east into the South American craton (Chiaradia et al., 2004; Glazner, 2022). Our results in Alaska suggest that these and other regions of long-lived arc localization reflect the geodynamic influence of upper-plate hydrodynamic "suction" on underlying slab geometry.

6 Conclusion

We document ca. 100 million years of magmatic arc spatial localization along the *ARZS* of the mobile southern Alaska Wrangellia composite terrane by compiling 6485 total bedrock and single grain detrital ages, in the framework of a trench that moves outboard through successive accretion events (Figures 5 and

7). For example, repeated periods of arc magmatism in the Central Alaska Range Arc, located at times >500 km from the trench, highlights a first-order upper-plate control on magmatic spatial patterns. By deduction, inherited features of the upper-plate must be controlling both the geometry (e.g., dip) of the underlying slab and potentially focuses melt transport. Arc localization since ca. 100 Ma has been in part controlled by inferred upper-plate related hydrodynamic (viscous) mantle wedge "suction" forces driven by trenchward motion of plates inboard of the Wrangellia composite terrane with thick-cold lithosphere (>100 km and up to 200 km thick) (Figure 8).

There has been a justified geoscience community focus on trench-perpendicular magmatic arc migration (e.g., Gianni and Luján, 2021) due to the dynamic nature of convergent margins and the important processes related to slab rollback and advance that arc migrations reflect. Conversely, magmatic arc localization may be an underappreciated geodynamic process with implications for first-order upper-plate control on slab geometry and magma ascent processes. Hence, we recommend time-dependent numerical modeling to further evaluate the influence of these hydrodynamic "suction" forces on the shallow subduction geometry of the Yakutat oceanic plateau. Additionally, matching gaps in arc magmatism along North America's western margin with the magmatic record of the Wrangellia composite terrane may provide further buttressing for the established "Baja-Alaska" paradigm (e.g., Tikoff et al., 2022; Boivin et al., 2022).

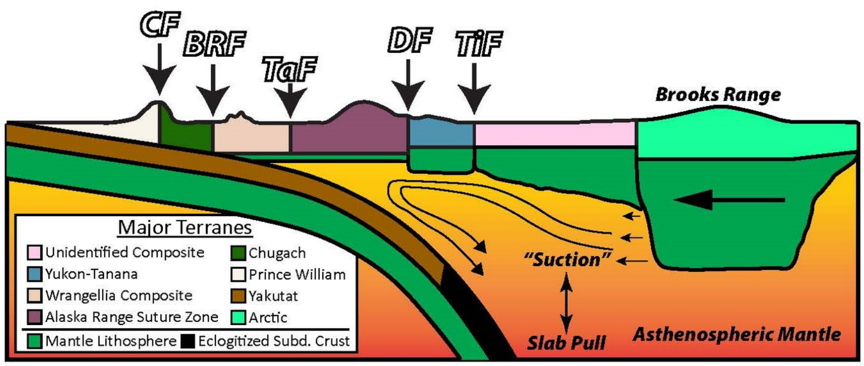

Figure 8. Schematic depiction of the current Alaska eastern subduction zone and interpretation of mantle flow and resultant mantle-flow-related hydrodynamic "suction" in the mantle wedge relative to the trench encroaching craton. Thicknesses are approximate-see figure 7 caption for references. Not to scale.

Acknowledgements

We would like to acknowledge Chris Nye for inspiring this work with a dissertation defense question and we thank Jeff Trop and Matt Brueseke for helpful discussions on the subject of southern Alaska's magmatic history. This work was partially funded by NSF EAR-2053042 and Woods Hole Oceanographic Institution OBS Instrument Center Postdoctoral Scholarship to Michael Everett Mann.

Availability Statement

The data is available in the supporting information files and can also be accessed in the Zenodo Repository (https://zenodo.org/record/7592004#.Y9mhhK3MK3A).

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