Focused rock uplift above the subduction décollement at Montague and Hinchinbrook Islands, Prince William Sound, Alaska

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ABSTRACT

Megathrust splay fault systems in accretionary prisms have been identified as conduits for long-term plate motion and significant coseismic slip during subduction earthquakes. These fault systems are important because of their role in generating tsunamis, but rarely are emergent above sea level where their long-term (million year) history can be studied. We present 32 apatite (U-Th)/He (AHe) and 27 apatite fission-track (AFT) ages from rocks along an emergent megathrust splay fault system in the Prince William Sound region of Alaska above the shallowly subducting Yakutat microplate. The data show focused exhumation along the Paton Bay megathrust splay fault system since 3–2 Ma. Most AHe ages are younger than 5 Ma; some are as young as 1.1 Ma. AHe ages are youngest at the southwest end of Montague Island, where maximum fault displacement occurred on the Hanning Bay and Paton Bay faults and the highest shoreline uplift occurred during the 1964 earthquake. AFT ages range from ca. 20 to 5 Ma. Age changes across the Montague Strait fault, north of Montague Island, suggest that this fault may be a major structural boundary that acts as backstop to deformation and may be the westward mechanical continuation of the Bagley fault system backstop in the Saint Elias orogen. The regional pattern of ages and corresponding cooling and exhumation rates indicate that the Montague and Hinchinbrook Island splay faults, though separated by only a few kilometers, accommodate kilometer-scale exhumation above a shallowly subducting plate at million year time scales. This long-term pattern of exhumation also reflects short-term seismogenic uplift patterns formed during the 1964 earthquake. The increase in rock uplift and exhumation rate ca. 3–2 Ma is coincident with increased glacial erosion that, in combination with the fault-bounded, narrow width of the islands, has limited topographic development. Increased exhumation starting ca. 3–2 Ma is interpreted to be due to rock uplift caused by increased underplating of sediments derived from the Saint Elias orogen, which was being rapidly eroded at that time.

INTRODUCTION

Flat-slab subduction and collision of the Yakutat microplate have had a profound effect on southern Alaskan geology for the past ~24 M.y. (e.g., Haeussler, 2008). Deformation from this interaction has penetrated as far as ~900 km inland, from the Brooks Range in the north (O’Sullivan et al., 1997a, 1997b) to the Saint Elias Mountains in the southeast. Flat-slab subduction of the Yakutat microplate has resulted in slip and deformation along several fault systems throughout the region (Fig. 1), including faults that splay off the subduction megathrust (e.g., Plafker, 1967; Bruhn et al., 2004; Haeussler et al., 2011; Liberty et al., 2013). Megathrust splay faults elsewhere in the world develop in accretionary prisms at outer ridges that flank the deformation front in subduction settings (e.g., Kame et al., 2003; Ikari et al., 2009). Some megathrust splay faults have been identified as conduits for long-term plate motion and significant coseismic slip during subduction earthquakes (Park et al., 2002; Kame et al., 2003, Moore et al., 2007; Ikari et al., 2009). These megathrust splay faults can be a source of tsunami generation during large megathrust ruptures, because they are typically located offshore in deep water.

Thermochronometers allow us to place million-year timescale constraints on the exhumation history of an area and to gain insight into structural systems, such as megathrust splay faults, as they accommodate the vertical transport of rock. Numerous studies using low-temperature thermochronology have focused on exhalation patterns across major fault systems associated with flat-slab subduction in southern Alaska, including studies in the Alaska Range (e.g., Fitzgerald et al., 1995; Haeussler et al., 2008, 2011; Benowitz et al., 2011, 2012, 2013), Chugach Mountains (Little and Naeser, 1989; Buscher et al., 2008; Arkle et al., 2013), and Saint Elias Mountains (e.g., Berger et al., 2008a, 2008b; Berger and Spotila, 2008; Meigs et al., 2008; Enkelmann et al., 2008, 2009; Spotila and Berger, 2010). Some of these studies detected loci of rapid exhumation, particularly in the Saint Elias and western Chugach Mountains, which may be the result of crustal-scale lithologic backstops to upper crustal rock deformation above the subducting Yakutat microplate. This study targets the southern Prince William Sound region (Fig. 1), located on the overriding North American plate closest to the Aleutian Trench and ~20 km above the megathrust décollement. Seismic imaging and thermal-mechanical models show that there is a large degree of coupling and/or underplating between the subducting Yakutat microplate and the overriding North American plate (Brocher et al., 1991; Ratchkovski and Hansen, 2002; Zweck et al., 2002; Ferris et al., 2003; Eberhart-Phillips et al., 2006; Fuis et al., 2008) below Prince William Sound, making this area susceptible to large (moment magnitude, Mw > 8.0) earthquakes like the 1964 Mw 9.2 Alaska earthquake (Plafker, 1965). Evidence that this region is actively accommodating deformation is shown by the tectonic analysis of ground breakage and surface warping during the 1964 earthquake on Montague and Hinchinbrook Islands (Plafker, 1967) in southern Prince William Sound. This study expands on Plafker’s (1967) original...
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gologic analyses by using apatite (U-Th)/He (AHe) and fission-track (AFT) thermochronology in order to quantify long-term rock uplift and exhumation patterns across southern Prince William Sound. We target Hinchinbrook and Montague Islands (Figs. 1 and 2), which are the largest and most trenchward islands in Prince William Sound.

TECTONIC AND GEOLOGIC SETTING

Cretaceous–Cenozoic History of Southern Alaska

The rocks along the southern Alaska margin in Prince William Sound are part of a vast accretionary complex that has developed since the early Mesozoic (e.g., Plafker et al., 1994; Bradley et al., 2003). The Yakutat terrane is the youngest in the terrane sequence and is composed mostly of a 15–30-km-thick oceanic plateau (e.g., Christeson et al., 2010; Worthington et al., 2012). Arrival of thickened Yakutat crust at the convergent boundary is inferred to have begun ca. 12–10 Ma (Plafker, 1987; Plafker et al., 1994; Zellers, 1995; Ferris et al., 2003; Eberhart-Phillips et al., 2006; Enkelmann et al., 2008, 2009) and as early as ca. 30–18 Ma (Plafker et al., 1994b; Enkelmann et al., 2008; Haeussler, 2008; Finzel et al., 2011; Benowitz et al., 2011, 2012; Arkle et al., 2013). As the collision of this relatively buoyant material progressed, a fold-thrust belt developed, leading to high topography in the eastern Chugach–Saint Elias Mountains, and a marked transition between shallow subduction beneath the Prince William Sound and relatively steeper subduction of dense oceanic Pacific plate to the southwest (Fig. 1). Sediment shed from the growing orogen also became incorporated into and deformed within the fold-thrust belt (e.g., Plafker, 1987; Meigs et al., 2008; Pavlis et al., 2012).

The accretionary complex rocks in central and southern Prince William Sound consist of the late Paleocene to Eocene Orca Group. This is a flysch deposit consisting dominantly of slate and graywacke turbidites, but it also contains interbedded conglomerate, volcanic-lithic and/or pelagic sandstone, and mudstone (Nelson et al., 1985). The Orca Group extends laterally for more than 100 km and has a structural thickness

Figure 1. Regional 300 m digital elevation model base map of southern Alaska (modified from the U.S. Geological Survey data repository, http://ned.usgs.gov). Prince William Sound study area is outlined by yellow box and shows the area of Figure 2. Major faults are after Plafker et al. (1994) and the U.S. Geological Survey data repository (http://ned.usgs.gov). Plate motion vectors (white arrows) are from Plattner et al. (2007) and Elliott et al. (2010). Interpreted region of the subducted Yakutat microplate (green boundary) and subaerial region of Yakutat microplate (green shaded portion of plate) are from Fletcher and Freymueller (2003), Eberhart-Phillips et al. (2006), and Fuis et al. (2008). CM—Chugach Mountains; KM—Kenai Mountains; SEM—Saint Elias Mountains; PZ—Pamplona fold-thrust zone; KIZ—Kayak Island zone; MG—Malaspina Glacier; BG—Bering Glacier; BF—Bagley fault; CSEF—Chugach–Saint Elias fault; MI—Montague Island; HI—Hinchinbrook Island; MSF—Montague Strait fault; MDI—Middleton Island. Modified from Arkle et al. (2013).
Intrusions were likely formed from near-trench processes related to a slab window, which may be associated with the subduction of the Kula-Farallon-Resurrection spreading center and possibly another smaller ridge (Bradley et al., 2003; Haeussler et al., 2003; Cowan, 2003; Cole et al., 2006; Madsen et al., 2006). Based on the timing of intrusion of these plutons and detrital zircon fission-track and U-Pb ages, the depositional age for the Orca Group is ca. 35 Ma in southeastern-most Prince William Sound, ca. 40–37 Ma near Latouche and Evans Islands, and ca. 60–57 Ma in central Prince William Sound (Garver et al., 2012; Davidson et al., 2011) (Fig. 2). Rocks of the Orca Group young to the southeast, toward the convergent margin.

Figure 2. Sample map with apatite (U-Th)/He (AHe), apatite fission-track (AFT), and zircon fission-track (ZFT) cooling ages. Base map (300 m digital elevation model) is modified from Arkle et al. (2013). Faults (solid lines), inferred faults (dashed lines), and overlain major lithologic units are from Plafker et al. (1989) and the U.S. Geological Survey fault data repository (http://ned.usgs.gov). The Patton Bay and Hanning Bay faults are highlighted in red. Transect lines are located for Figures 5 and 6. MI—Montague Island; HI—Hinchinbrook Island; HKI—Hawkins Island; LI—Latouche Island; KNI—Knight Island; NI—Naked Islands; GI—Green Island; SI—Smith Islands; PE—Port Etches; ZB—Zaikof Bay; RB—Rocky Bay; PB—Patton Bay; JC—Jeanie Cove.

of 18–20 km (Brocher et al., 1991; Plafker and Berg, 1994; Fuis et al., 2008). It was intruded by two episodes of small granitic plutons that are between ca. 56–53 Ma (the Sanak-Baranof belt) and ca. 40–37 Ma (the Eshamy suite) (Hudson et al., 1979; Plafker and Berg, 1994; Haeussler et al., 1995; Davidson et al., 2011; Garver et al., 2012, 2013; Carlson, 2012; Johnson, 2012).
Regional Structures of Prince William Sound

Our study area in Prince William Sound is bound to the north by the Chugach Mountains and to the south by Hinchinbrook and Montague Islands (Fig. 1). The arcuate Contact fault strikes approximately east-west in north-central Prince William Sound and bends southward in the Chugach Mountains to form the western Chugach syntaxis, a major structural boundary to this study area. In its southern exposures the Contact fault strikes southwest and generally separates Prince William Sound from the Kenai Peninsula (Fig. 1). The Contact fault is dominantly a right-lateral strike-slip fault to the east (Bol and Roeske, 1993), but displays reverse-fault dip-slip displacement to the west in the Chugach Mountains and Prince William Sound (Bol and Gibbons, 1992). Farther toward the trench an array of faults extends southwest from the Cordova area (Fig. 2) to form the faults of Montague and Hinchinbrook Islands (Nelson et al., 1985), all of which strike northeast-southwest and dip northwest. These are the most outboard faults exposed in Prince William Sound (Fig. 2). Between these faults and the Contact fault is the Montague Strait fault, which is a high-angle normal fault that dips southeast, though the deep structural configuration of the fault is uncertain (Haeussler et al., 2014; Liberty et al., 2013). Liberty et al. (2013) interpreted the Montague Strait fault as a major structure that separates metamorphosed Orca Group rocks to the northwest from unmetamorphosed Orca Group rocks to the south (Liberty and Finn, 2010; Haeussler et al., 2014; Garver et al., 2012). It was previously recognized as a structural discontinuity (Nelson et al., 1985), but the nature of the fault was unknown. Subsequent National Oceanic and Atmospheric Administration multibeam surveys collected from 1988 to 2003 reveal a seafloor fault scarp (Liberty and Finn, 2010; Haeussler et al., 2014). New seismic reflection profiles show that the Montague Strait fault locally had southeast-side-down normal slip during the Holocene (Liberty and Finn, 2010; Haeussler et al., 2014; Liberty et al., 2013). Focused rock uplift at Montague and Hinchinbrook Islands

Hinchinbrook and Montague Islands

Hinchinbrook and Montague Islands are elongate, narrow islands with steep coastlines and numerous reverse faults that strike parallel to the trend of the islands (Pfaffker, 1967) (Fig. 2). Average peak elevations on Hinchinbrook and Montague Islands are consistently ~800 m; the highest peaks are nearly 1000 m. Bedding is highly deformed and ranges from shallowly dipping to vertical and is overturned in some places (Nelson et al., 1985; Pfaffker, 1967). In low-lying areas, unconsolidated Quaternary glacial till with variable thicknesses is present.

There are two main reverse faults on southern Montague Island, the Patton Bay and Hanning Bay faults, both of which ruptured during the 1964 earthquake (Pfaffker, 1967). After the earthquake, the faults were traceable on land by large (6–9 m) fault scarps, landslides, and uplifted coastal platforms (Pfaffker, 1967). These faults generally strike northeast, or parallel to the long axis of the island, and dip ~60° northwest on average (Pfaffker, 1967) (Fig. 2). The Patton Bay fault can be traced on land for 35 km along the southeast coast and continues southwest on the seafloor, perhaps as far south as Kodiak Island (Pfaffker, 1965; Liberty et al., 2013). Seismic reflection profiles and bathymetry show the Patton Bay fault continuing offshore to the southwest for ~20 km (Pfaffker, 1967; Malloy and Merrill, 1972), where vertical displacements of ~15 m associated with the 1964 earthquake are mapped along seafloor escarpments (Malloy and Merrill, 1972; Liberty and Finn, 2010; Liberty et al., 2013). To the north, the Patton Bay fault may continue offshore along the coast to the near the northeast end of the island, where its trace is lost and the fault is likely broken into multiple strands (Fig. 2). The northern coastal extent of the Patton Bay fault is suggested by the straight nature of the coastline and numerous triangular facets that line the coast along northeastern Montague Island. However, there is little evidence of active faulting at the northern extent of the Patton Bay fault. Mountain-front sinuosity is nearly 1.0 and average slopes are steeper on the east coast (18°–22°) versus the west coast (10°–12°) (measurements from this study). Motion on the fault at its southern extent was dominantly dip slip with a maximum of 9 m of vertical offset on land during the 1964 earthquake, although there was a small component (~0.5 m) of left-lateral motion (Pfaffker, 1967).

The Hanning Bay fault, which cuts across a small portion of the southwest coast of Montague Island at Fault Cove (Fig. 2), extends for ~6 km on land with the same structural orientation as the Patton Bay fault. The well-defined 1964 scarp at Fault Cove has a vertical offset of 6 m (Pfaffker, 1967). Across both the Hanning Bay and Patton Bay faults, the northwest blocks were upthrown relative to the southeast blocks during the 1964 earthquake. The block southeast of the Patton Bay fault was upthrown ~4.7 m relative to sea level, the block northwest of the Patton Bay fault was upthrown ~12 m, and the block northwest of the Hanning Bay fault was upthrown ~5 m (Pfaffker, 1967).

Liberty et al. (2013) showed the presence of an additional splay fault, the Cape Cleare fault, offshore and southwest of Montague Island. Bathymetry shows a 40 m fault scarp, and subsequent marine terrace ~5 km south of the Patton Bay fault that decreases in height to the southwest and forms the hanging-wall block of the Cape Cleare fault. This fault is traced onshore south and east of the Patton Bay fault (Fig. 2).

Other geophysical evidence from Trans-Alaska Crustal Transect (TACT) studies (e.g., Fuis et al., 2008) shows that faults in the inlet between Hinchinbrook and Montague Islands near Zaikof Bay become listric and are connected at their base to the subduction décollement to the northwest. These faults are along strike with those on Hinchinbrook and Montague Islands, possibly indicating that the faults on Hinchinbrook and Montague Islands are also rooted at depth (Liberty et al., 2013; Haeussler et al., 2014). Land surfaces at Montague Island, along the footwall block of the Cape Cleare fault offshore, and at Middleton Island ~100 km southeast toward the Aleutian megathrust (Fig. 1), were all uplifted during the 1964 earthquake, suggesting that these faults are likely rooted downward and are separately linked to the décollement at depth (Pfaffker, 1967; Malloy and Merrill, 1972; Haeussler et al., 2014).

PREVIOUS REGIONAL THERMOCHRONOLOGY WORK

An extensive data set of low-temperature thermochronometer ages generated over the past 25 years provides insights into the timing, rates, and regional exhumation patterns, and provides constraints on regions of localized rapid exhumation during the Neogene along the southern Alaska margin (e.g., O’Sullivan et al., 1997a, 1997b; Meigs et al., 2008; Berger et al., 2008a, 2008b; Armstrong et al., 2008; Buscher et al., 2008; Enkelmann et al., 2008, 2009; Spotila and Berger, 2010; Arkle et al., 2013).

In the Saint Elias region, exhumation rates in the past ~6 m.y. are between ~0.5 and 4 mm/yr and vary based on structural position relative to major fault systems (Berger et al., 2008a, 2008b; Berger and Spotila, 2008; Meigs et al., 2008; Enkelmann et al., 2008, 2009; Spotila and Berger, 2010; Falkowski et al., 2014). Low-temperature cooling ages are generally very young (AHe younger than 1.5 Ma) along the coast and abruptly increase north of the Bagley fault, suggesting that the Bagley fault is acting as a deformational backstop to thin-skinned folding and thrusting at the collision front (Berger et al., 2008b; Berger and Spotila, 2008; Enkelmann et al., 2008, 2009; Headley et al., 2013; Pavlis, 2013) (Fig. 1). South of the Bagley fault, young AHe ages are attributed to their position within the active fold-thrust belt coupled with exten-
sive erosion at the coastal front due to its windward position and heavy glaciation (Spotila and Berger, 2010). This zone of focused exhumation is projected west along the Bagley-Contact backstop toward the Miles Glacier region, or Miles Corner (previously referred to as the Western or Katalla syntaxis; e.g., Chapman et al., 2011), where it curves southwest to eventually connect with the Ragged Island thrust, Kayak Island zone, and the Alaska-Aleutian megathrust (Spotila and Berger, 2010) (Fig. 1). While the Miles Corner region may represent an immature indenter corner, there have been insufficient age constraints across the Copper River delta and into Prince William Sound to show whether this zone of rapid exhumation continues west (Fig. 1).

In the western Chugach Mountains and northern Prince William Sound (Fig. 1), a bullseye of relatively rapid exhumation was identified in a syntaxial bend between the Border Ranges and Contact faults (Arkle et al., 2013). AHe and AFT ages decrease northward across the Contact fault to minimum ages (averaging ca. 5 and 10 Ma, respectively) in the core of the Chugach Mountains between the Contact and Border Ranges faults. Zircon fission-track (ZFT) ages follow a similar pattern, but with older and more scattered ages, ranging between ca. 50 and 26 Ma (transect D–D'; Figs. 1 and 3) (Little and Naeser, 1989; Arkle et al., 2013). Between the Montague Strait and Contact faults, ages for all thermochronologic systems generally decrease by 50% relative to north of the Contact fault (Fig. 3). This pattern of relatively young ages and rapid exhumation north of the Contact fault is interpreted to be the result of underplating along the décollement that has been focused by a syntaxial geometry and modulated by glacial erosion at the southward flank of the core (Arkle et al., 2013).

The data set from this study helps to constrain the nature of deformation west of the transition from the eastern Chugach–Saint Elias Mountains and across the Copper River delta into Prince William Sound. It also provides

![Figure 3. Plot of thermochronometer ages along a southeast-northwest transect (D–D') shown in Figure 1. Ages are projected onto the transect profile from a 100 km swath. Age uncertainties are ±1σ. Samples are shown relative to faults (vertical dashed lines). Shaded regions mark approximate bounds of maximum and minimum ages for the apatite (U-Th)/He (AHe), apatite fission-track (AFT), and zircon fission-track (ZFT) systems. Direction of Yakutat convergence is from right to left. The ZFT ages in the Chugach Mountain region are the average of the two youngest ZFT age peaks from modern glacial deposits (Arkle et al., 2013). Figure modified from Arkle et al. (2013).](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/11/1/144/3333341/144.pdf)
constraints on deformation mechanisms above the subduction megathrust, but outboard of the exhumation bullseye and syntaxial bend in the western Chugach Mountains.

METHODS

This study utilizes AHe and AFT thermochronometers to track thermal histories up to effective closure temperatures of ~130 °C. For the AHe system, the partial retention zone (PRZ) is between ~40 °C and 70 °C (depending on the cooling rate, grain size, and effective uranium concentration), which corresponds with depths of ~2–3 km at typical geothermal gradients and surface temperatures (Farley, 2000; Farley and Stockli, 2002; Ehlers and Farley, 2003; Reiners et al., 2004; Flowers et al., 2009). For the AFT system, tracks anneal at temperatures between 60 °C and 130 °C (e.g., Wagner and Reimer, 1972; Naeser, 1979; Gleadow et al., 1986; Dumitru, 2000; Donellick et al., 2005), which corresponds to depths of ~3–6 km (depending on annealing kinetics and geothermal gradient).

We also utilize ZFT data from other studies (Carlson, 2012; Garver et al., 2012) that track the thermal histories of rock up to ~240 °C (e.g., Reiners and Brandon, 2006).

Sampling Strategy and Analytical Techniques

Samples of Orca Group sandstone (n = 32) were collected in southeastern Prince William Sound and used for AHe and AFT analysis (Fig. 2; Table 1). Samples were collected both along and across the structural grain of Hinchinbrook and Montague Islands and especially adjacent to known faults and along the length of topography from southern Montague Island to north of Cordova. At least 5 kg of unweathered sandstone was collected in order to ensure sufficient apatite yield. Most samples were medium- to coarse-grained sandstone with well-sorted angular to subangular clasts, composed of quartz, feldspar, lithic fragments, and minor biotite. AHe ages were determined for 32 samples by laser and inductively coupled plasma–mass spectrometry methods at the California Institute of Technology (Pasadena). We used 141 single apatite grains with 4–7 single grain replicates per sample for AHe analysis. Of these grains, 13 (9%) were removed from the average age calculations because they yielded outlier ages that were high (greater than a 2σ variance) relative to the other grains in the samples (Table SF1 in the Supplemental File). Anomalously high ages are probably due to high U-bearing inclusions.

TABLE 1. SUMMARY OF THERMOCRONOMOLGY DATA

<table>
<thead>
<tr>
<th>Sample</th>
<th>Elevation (m)</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Age* (Ma) ±1σ (Ma) ε rate (mm/yr)</th>
<th>AHe age data</th>
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*Note: All samples are Orca Group sandstone. Latitude and longitude are North American Datum 1927. Dashes indicate no data.*

††Ages are from Arkle et al. (2013).

**Apatite (U-Th)/He (AHe) ages are averages of valid replicates after Ft correction and are reported as a weighted mean (discussed in Supplemental File [see text footnote 1]).

§n is number of single grain replicates used for AHe age calculation.

*Apatite fission-track ages are reported from analytical data (Table SF2 in the Supplemental File [text footnote 1]).

ε is exhumation rate for both AFT and AHe; data are from Tables SF3 and SF4 in the Supplemental File (text footnote 1) and are derived from age and closure temperature data.

††Ages are from Arkle et al. (2013).
undetected within the crystal. To evaluate the effects of radiation damage, effective uranium concentration was compared with each single-grain age (e.g., Flowers et al., 2009), but no relationship was apparent (Fig. SF1 in the Supplemental File [see footnote 1]). An Ft (alpha ejection) correction was applied to all raw ages to account for alpha ejection effects related to the grain size and shape (Farley et al., 1996; Farley, 2002). After outlier ages were culled, a weighted average AHe age was determined for the 32 samples using the 4–7 same-sample replicates remaining and a 1 σ confidence interval (see the Supplemental File [footnote 1] for details regarding weighted age calculations).

AFT ages were determined for 27 samples using the external detector method (e.g., Gleadow and Duddy, 1981) and ages were computed using Trackkey version 4.2 (Dunkl, 2002). Analytic data are reported in Table SF2 in the Supplemental File (see footnote 1). Fission tracks were counted in 35–40 grains in most samples; as few as 15 grains were counted in some samples with low apatite yield or poor polishing. The etch pit width (Dpar) varies from 0.93 to 1.75 µm and the average for all samples is 1.48 ± 0.29 µm. No systematic relationship was found between Dpar and AFT single-grain age, indicating that age variation between samples is not caused by varying kinetic properties (Table SF2 in the Supplemental File [see footnote 1]). Almost all have narrow single-grain age distributions and pass the P(χ²) (>5%) test, indicating that the grains either spent little time in the partial annealing zone and/or are kinetically invariant.

Horizontal confined track length measurements were made for three samples (Table 1). Horizontal confined tracks were generally difficult to find within grains due to low spontaneous track densities, despite undergoing Cf-252 irradiation. In 2 samples, an average of 16 measurable tracks was counted, and in 1 sample, 108 horizontal-confined tracks were counted. The range in average track lengths is 13.0–13.8 µm.

RESULTS

AHe Ages

New AHe ages range from 11.2 to 1.1 Ma (Table 1; Table SF1 in the Supplemental File [see footnote 1]). In samples collected across the topographic grain on Hinchinbrook and Montague Islands, young ages are found both at sea level and at high elevations, indicating no apparent age-elevation relationship. Samples north of the Montague Strait fault have AHe ages of 7.2 ± 1.4 and 11.2 ± 1.9 Ma (Figs. 2 and 4; Table 1) and are consistent with previous AHe ages in central Prince William Sound (Arkle et al., 2013) that average 12.5 Ma. Just south of the Montague Strait fault, three ages on Smith Islands and Green Island are between 6.9 and 4.7 Ma (Fig. 2). The youngest ages are on southern Montague Island and range from 6.3 to 1.1 Ma, with an average age of 2.9 Ma. On northern Montague Island, five samples have ages between 4.5 and 3.0 Ma, with an average of 3.9 Ma. On Hinchinbrook Island, 10 AHe ages range from 8.4 to 3.6 Ma, with an average age of 5.4 Ma (Fig. 2). Farther northeast, three ages are between 4.9 and 4.1 Ma on Hawkins Island and just north of Cordova (Fig. 2). All AHe ages are younger than the sample depositional age of ca. 35 Ma (Garver et al., 2012; Carlson, 2012), and are reset.

AFT Ages

AFT ages range from 21.5 to 4.4 Ma across southern Prince William Sound (Table 1; Table SF2 in the Supplemental File [see footnote 1]). AFT ages north of the Montague Strait fault are 16.6 ± 1.8 and 21.5 ± 2.1 Ma (Fig. 2; Table 1), and are consistent with the 37.4–10.0 Ma AFT ages of Kveton (1989) and Arkle et al. (2013) between the Contact and Montague fault systems (Fig. 4). Three samples just south of the Montague Strait fault have AFT ages between 17.8 and 11.2 Ma. Those on southern Montague Island are, on average, 8.9 Ma and range from 18.7 to 4.4 Ma. On northern Montague Island, AFT ages range from 11.4 to 6.3 Ma and average 9.1 Ma. On Hinchinbrook Island the average AFT age is 10.6 Ma, and ranges from 13.9 to 7.5 Ma (Fig. 2). Two samples north of Cordova have AFT ages of 9.4 and 10.3 Ma. Like their corresponding AHe ages, all of the AFT ages are younger than the ca. 35 Ma depositional ages and have been reset.

DISCUSSION

Local Analysis of Thermochronometer Ages and Relationships to Faults

Our new data show that AHe and AFT ages south of the Montague Strait fault are younger than those from rocks in the core of the Chugach Mountains to the north (Fig. 3). Overall, ages decrease by ~10–15 m.y. (~50% for the AHe and AFT systems) southward across the Montague Strait fault, similar to the age decrease north of the Contact fault (Fig. 3). ZFT ages (Carlson, 2012), however, are the same or increase southward across the Montague Strait fault (Fig. 3). The ZFT ages (averaging ca. 52 Ma; Carlson, 2012) southeast of the Montague Strait fault are older than the 35 Ma depositional age for the Orca Group sandstone in this region (Hilbert-Wolf, 2012), indicating that these rocks were never buried deep enough to be reset.

AHe ages young southward along the strike of Hinchinbrook and Montague Islands long axes; the youngest ages are at southern Montague Island (transect A–A′; Figs. 2 and 5). However, there is the exception of two older ages on southern Montague Island and one older age on northeastern Hinchinbrook Island (open symbols in Fig. 5). The older AHe ages (5.8 and 6.3 Ma) on Montague Island are located on the footwall block of the Cape Cleare fault (Figs. 4 and 5), indicating that those rocks were never exhumed as rapidly as other southwestern Montague Island rocks. Similarly, the sample on northeastern Hinchinbrook Island has a significantly older AHe age (8.4 Ma) than adjacent samples, and it is located along strike with the Cape Cleare fault farther south (Figs. 4 and 5). We infer these relatively older ages to be part of a separate structural block that was exhumed more slowly than rocks northwest of the Cape Cleare fault and northwest of the structure on northeastern Hinchinbrook Island.

In contrast to the AHe age trends, there is no systematic northeast to southwest AFT age trend (Fig. 5). The lack of an AFT age trend suggests that exhumation was relatively uniform along the islands while rocks were cooling through the AFT closure temperature.

Distinct changes in AHe and AFT age patterns also occur across known faults (Fig. 6). AHe and AFT ages decrease southward by more than half across the Montague Strait and Hanning Bay faults in the southwest Montague Island area (transect B–B′; Figs. 2 and 6A). However, this age change is across a broad ~25 km region and may be related to regional rock uplift and exhumation variations rather than offset slip across the Montague Strait fault. Farther southeast across the Patton Bay fault, an average ~1.5 m.y. increase in AHe ages and average ~4.5 m.y. increase in AFT ages from the hanging-wall block to the footwall block may indicate significant changes in rock uplift along the Patton Bay fault in the past ~5 m.y. The contrast in ages across the Hanning Bay, Patton Bay, and Cape Cleare faults since the late Miocene indicates that these structures have been active on million-year time scales and have exhumed rocks from depths of >4 km along normal, fault-bounded blocks.

Faults and structural lineaments are more dispersed farther northeast on northern Montague and Hinchinbrook Islands, where there is a more complex network of faults (Fig. 2) (Nelson et al., 1985). Both AHe and AFT ages of samples from northern Montague and Hinchinbrook Islands decrease toward the southeast across the

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Montague Strait fault region (transect C–C′; Figs. 2 and 6B). AHe ages are ca. 5 Ma on both sides of the Rude River fault on Hinchinbrook Island, suggesting little differential exhumation across the fault in the past 5 m.y. AFT ages decrease to ca. 2.5 Ma to the southeast of the Rude River fault (Fig. 6B), but there is no definitive break in the AFT ages across the Rude River fault.

Cooling and Exhumation Rates

Cooling and exhumation rates for single samples were derived from sample-specific closure temperatures, an averaged geothermal gradient that accounts for thermal advection of rapidly cooled samples, assumed steady-state topography, and a surface temperature of 0 °C (Péwé, 1975). For the AFT ages, a closure temperature of 110 °C was assumed (Reiners and Brandon, 2006). Note that variations in the AFT closure temperature can result from variable kinetic parameters, but Dpar for samples in this study varies little. Closure temperatures for AHe ages were determined using the program CLOSURE (Brandon et al., 1998) using average spherical radii and cooling rates specific to each sample. The closure depth ($Z_c$) for each sample was calculated using a modified equation of Brandon et al. (1998):

$$Z_c = \left( \frac{T_c - T_s}{g_o} \right) + (h - h_m),$$  

where $h$ is the sample elevation, $h_m$ is the average elevation for a 10 km radius around the sample location, $T_s$ is the surface temperature, $T_c$ is the effective closure temperature, and $g_o$ is the geothermal gradient. The average elevation was computed to account for the effect of the long wavelength topography on the shape of shallow isotherms (Stüwe et al., 1994; Mancktelow and Grasemann, 1997).

For samples south of the Montague Strait fault, average cooling rates are ~6.5 °C/m.y. between AFT and AHe closure temperatures, and increase to ~16 °C/m.y. in the past 5 m.y. or less (line A, Fig. 7). On Montague Island, the average cooling rate is ~5 °C/m.y. between AFT and AHe closure temperatures, increasing to
~20 °C/m.y. after AHe closure (line B, Fig. 7). On the hanging-wall block of the Patton Bay fault on southern Montague Island, the average cooling rate is 6.5 °C/m.y. after AFT closure and increases to ~35 °C/m.y. after AHe closure (line C, Fig. 7). These relationships across southern Prince William Sound demonstrate a regional increase in cooling rate in the past ~5 m.y., or since the time of AHe closure. More locally, cooling rates increased between ca. 5 and 2 Ma for rocks on the hanging wall of the Patton Bay fault on southern Montague Island.

A background geothermal gradient ($g_i$) for southern Prince William Sound was computed based on the surface heat flow and thermal conductivity (Blackwell and Richards, 2004; Huang et al., 2008; Batir et al., 2013). Assuming a background surface heat flow for Prince William Sound of 45 mW/m² (Blackwell and Richards, 2004; Batir et al., 2013) and a thermal conductivity of 2.5 W/mK for typical fine-grained sedimentary rocks (Huang et al., 2008), we compute a $g_i$ of 18 °C/km. This background $g_i$ was then given a ±20% variability to account for variations in heat flow and thermal conductivity resulting in a range in $g_i$ values of 14.4–21.6 °C/km (see Supplemental File [footnote 1] for analysis).

Figure 5. Apatite (U-Th)/He (AHe) and apatite fission-track (AFT) ages projected onto line A–A′ parallel to Hinchinbrook and Montague Islands long axes (transect location shown in Fig. 2). Age uncertainties are ±1σ. Trend lines show a southward-younging of ages for the AHe system. Ages show no systematic variation from northeast-southwest for the AFT system. Hollow sample symbols are outlier ages on the footwall block of the Cape Cleare fault and southeastern Hinchinbrook Island (see text).

Figure 6. Cross sections across the Montague Strait fault and Montague and Hinchinbrook Islands (transect locations shown in Fig. 2), showing apatite (U-Th)/He (AHe) and apatite fission-track (AFT) ages relative to fault locations. (A) B–B′. (B) C–C′. Age uncertainties are ±1σ. Colored bands generally outline range in ages and red or blue line is average age for the region. Arrows along fault location markers (gray dashed lines) represent relative vertical displacement direction for that fault.
Regional processes may affect the thermal structure of the crust overriding the Yakutat microplate and may influence low-temperature cooling ages. These processes include ridge subduction during the Paleocene–Eocene (e.g., Haeussler et al., 2003; Idlemen et al., 2011; Benowitz et al., 2012) and later cooling related to subduction of the relatively cool Yakutat microplate. Thermal length arguments (e.g., Turcotte and Schubert, 2002) suggest that the transitory thermal effects of Paleocene–Eocene ridge subduction in the 25-km-thick overriding plate would have dissipated in ~15–20 m.y., prior to the Miocene and younger cooling documented by our ages. The present-day regional geothermal gradient is relatively low, but it is consistent with flat-slab subduction thermal models (e.g., Gutscher and Peacock, 2003) and models of thermal effects of subduction in general (e.g., Cloos, 1985). We use the relatively low present-day geothermal gradient in our exhumation analysis, but if the slab cooling effects were greater in the past, then the exhumation rates discussed here may be a minimum. The relatively young ages in our study and the local scale of the age variations suggest that regional slab refrigeration or ridge subduction effects do not cause the age patterns we observe, thus we assume that cooling is related to exhumation.

It is well known that the advection of hotter rocks toward the surface during exhumation causes geothermal gradients to increase (e.g., Kappelmeyer and Haenel, 1974; Powell et al., 1988; Ehlers, 2005). We apply a simple correction to the background geothermal gradient by assuming erosion durations consistent with sample ages and typical exhumation rates of between ~0.5 and 2 mm/yr. Advection corrections increase $g_i$ between 10% and 80%, resulting in sample-specific advection-corrected geothermal gradient ($g_i$) values between 23 and 38 °C/km (Tables SF3 and SF4 in the Supplemental File [see footnote 1]). The median of the two corrected end-member $g_i$ values for each sample was used in Equation 1 to compute the closure depth and the resulting exhumation rates ($\varepsilon = Z/t_i$) for each sample age ($t_i$) (Table 1).

For the AHe system, the average closure temperature for southern Prince William Sound is ~66 °C, average $Z_c$ is ~2.7 km, and overall average exhumation rates are 0.7 mm/yr. For the AFT system, a 110 °C closure temperature was used for all samples. The average depth to closure is ~4.5 km, and average exhumation rates are 0.4 mm/yr (Tables SF3 and SF4 in the Supplemental File [see footnote 1]). On the hanging wall of the Patton Bay fault of southern Montague Island, exhumation rates are as high as 2.5 mm/yr based on AHe closure, but average 1.5 and 0.6 mm/yr based on AHe and AFT closure, respectively. Overall, exhumation rates increased in the past ~5 m.y. or less (Fig. 7) across both Montague and Hinchinbrook Islands, but on southern Montague Island the exhumation rates increased in the past ~2 m.y.

**Timing and Magnitude of Rock Uplift across Faults**

AHe and AFT age differences or similarities across known faults on Montague and Hinchinbrook Islands allow estimates of relative rock uplift across the faults, and therefore estimates of long-term fault offset. Based on the AHe cooling age data, samples from the Patton Bay fault hanging wall cooled at a rate of 35 °C/m.y. since ca. 2 Ma, which is the average AHe age of the hanging-wall samples (Figs. 6A and 7). Samples from the footwall block of the Patton Bay fault cooled at a rate of 14 °C/m.y. since 3.3 Ma. Assuming constant cooling rates across the Patton Bay fault since 3.3 m.y. and an average geothermal gradient of 25 °C/km, the temperature change differential between the footwall and hanging-wall blocks is 65 °C, leading to a difference in rock uplift of ~2.6 km across the fault since 3.3 Ma. The Patton Bay fault is estimated to dip 60° based on surface ruptures from the 1964 earthquake (Plafker, 1967) and apparent dip estimates in the TACT Prince William Sound deep seismic reflection line (Haeussler et al., 2014; Liberty et al., 2013). Correcting for the 60° dip leads to a total offset of ~3 km across the Patton Bay fault since 3.3 Ma; note that total offset amounts are greater than the fault extension.
if the fault dip is less, as suggested by Liberty et al. (2013). AFT age similarity across the Patton Bay fault indicates that cooling rates were likely the same on the footwall and hanging-wall blocks while cooling through AFT closure, suggesting minimal differential exhumation across the Patton Bay fault between ca. 10 Ma (AFT closure) and 3.3 Ma (AHe closure).

On northern Montague and Hinchinbrook Islands, the clustering of AHe ages ca. 4.5 Ma allows estimates to be placed on the maximum amount of slip on these faults because vertical fault offset could not have been greater than the depth that corresponds to the minimum temperature of the AHe partial retention zone. Assuming an average advection-corrected geothermal gradient of 25 °C/km and a minimum PRZ temperature of 40 °C, the maximum amount of differential rock uplift is ~1.6 km in the past ~4.5 m.y. on northern Montague and Hinchinbrook Islands.

The depositional age for Orca Group sandstone (younger than 35 Ma; Hilbert-Wolf, 2012) in southern Prince William Sound is an important constraint because it indicates that the sediments were at surface temperatures after 35 Ma. If the AHe and AFT ages are reset, but the ZFT ages are not reset (Carlson, 2012), then the Orca Group had to have been buried to depths and corresponding temperatures of between ~110 °C and ~200 °C, then reexhumed after ca. 35 Ma (Fig. 7). The maximum AFT age is the minimum age that the rocks at Hinchinbrook and Montague Islands were at 110–200 °C. The shaded region in Figure 7 represents the range of cooling paths rocks may have taken prior to passing through AFT closure temperature. If the average AFT cooling rate (line A, Fig. 7) is constant from 200 °C, then this rate may be extrapolated to as long ago as ca. 23 Ma (dashed line, Fig. 7). We acknowledge that there is considerable uncertainty in this analysis, but it provides loose constraints on the potential timing of maximum temperature estimates for rocks on Montague and Hinchinbrook Islands. Given that rocks were buried to temperatures as high as 200 °C, the maximum amount of rock uplift and exhumation in southern Prince William Sound (assuming a constant average geothermal gradient of 25 °C/km) is ~8 km since ca. 23–35 Ma. In addition, the reset AFT ages indicate that the minimum exhumation magnitude on Montague and Hinchinbrook Islands is ~4.8 km, which occurred in the past ~7–10 m.y.

Regional Analysis

One of our goals is to examine the relationship between the zone of very young AHe ages (younger than 1 Ma) and rapid exhumation south of the Bagley fault in the Saint Elias region (Spotila and Berger, 2010) and the thermochronology data across the Copper River delta into Prince William Sound. Based on our new ages, the region of young cooling ages in the Saint Elias Mountains does not appear to extend westward into Prince William Sound (Fig. 8), but rather bends southward at the Miles Corner to connect with the Kayak Island zone and Aleutian megathrust, as suggested by
Spotila and Berger (2010) (red dashed area, Fig. 8). In this interpretation, the Kayak Island zone and Ragged Mountain fault link the Miles Corner region with the Aleutian megathrust and are well-defined boundaries between transpression and convergence. Even though the band of youngest ages either ends at Miles Corner or bends south, some focused rock uplift may be transferred west into Prince William Sound, because rocks with young ages (4 Ma AHe) continue west across the Copper River delta into the Hinchinbrook and Montague Islands region. The rapid exhumation in the Saint Elias region is focused along the Bagley backstop (Berger et al., 2008b). We propose that this backstop continues westward as the Montague Strait fault (Fig. 8), but with lower exhumation rates than in the Saint Elias orogen. A broader zone of deformation extending from the Kayak Island fault system to southern Prince William Sound (area A, Fig. 8) may also accommodate the overall rock uplift and exhumation differences south of the backstop in southern Prince William Sound and the Saint Elias area. Uplifted fault blocks during the 1964 earthquake and the presence of reverse faults (Haeussler et al., 2014) outboard of southern Prince William Sound (e.g., Meigs and Sauber, 2000; Spotila et al., 2004). In the Saint Elias Mountains, where glaciers cover much of the windward flank of the orogen, the coincidence of the ELA with zones of rapid exhumation suggests that glaciers partly control the rock uplift and exhumation (Meigs and Sauber, 2000; Spotila et al., 2004; Berger and Spotila, 2008; Berger et al., 2008a, 2008b).

Our data from Montague and Hinchinbrook Islands show a lack of correlation between AHe age (or exhumation rates and magnitudes derived from the ages) and elevation. Computed exhumation magnitudes along the trend of Montague and Hinchinbrook Islands were derived using the AHe exhumation rates and an exhumation duration of 2 m.y. (Fig. 9); the duration is based on the average AHe age of samples from the Patton Bay fault hanging wall. In general, exhumation magnitude increases from northeast to southwest, with highest exhumation magnitudes at the south end of Montague Island (Fig. 9). Range-crest elevations along the island-parallel transect are ~800 m on both Hinchinbrook and Montague Islands, but exhumation decreases to below sea level between them at Hinchinbrook Entrance (the inlet between Hinchinbrook and Montague Islands). Exhumation magnitude is relatively constant along the transect, even across Hinchinbrook Entrance. At the southern end of Montague Island, elevation decreases to sea level whereas the exhumation magnitudes increase abruptly (Fig. 9). We expect that elevation would be greatest at the south end of Montague Island because it has the highest exhumation rate and is not a focus region of high orographic precipitation or the alpine glacier–dominated windward flank of an orogen. The lack of coincidence between high exhumation magnitude (or rate) and high-elevation regions has been documented in other areas, especially where Quaternary glaciers eroded the landscape. In central and northern Fiordland, New Zealand, AHe ages are typically 1–3 Ma, but elevations are <1500 m (House et al., 2005). House et al. (2005) interpreted the changes in ages across Fiordland to be due to differential exhumation across faults, but extensive glaciation caused regional erosion across the faults after ca. 2 Ma (Sutherland et al., 2009). Along the Fairweather corridor adjacent to the Fairweather fault in southeast Alaska, AHe ages are typically younger than 1 Ma (McAleer et al., 2009) across 50 km regions of low topography that are relatively glacially denuded. McAleer et al. (2009) suggested that glacial erosion in the Fairweather corridor was high enough to limit the development of topography even where exhumation rates were highest. Whereas Hinchinbrook and Montague

Figure 9. Plot comparing island-parallel topographic profile (gray dashed line, transect A–A’ from Fig. 2) and sample exhumation magnitudes (green triangles). Exhumation magnitudes represent exhumation for past 2 m.y. at sample-specific exhumation rates. Elev.—elevation.
Islands are not currently glacially dominated or a focus region of high orographic precipitation; Pleistocene glaciers extended ~100 km south of their present location (Kaufman and Manley, 2004). Thus, we infer that glaciers were able to erode Montague and Hinchinbrook Islands rapidly enough to limit topographic growth even where rock uplift rates were the highest, attesting to the buzz saw potential of glaciers (e.g., Brozović et al., 1997; Meigs and Sauber, 2000; Spotila et al., 2004).

Although glacial erosion likely limited topographic growth, the maximum elevations are probably also limited by the narrowness of rock uplift along the splay faults. Both Hinchinbrook and Montague Islands are at most 20 km wide, and <10 km in many locations. For example, AHe ages on the Yucaipa Ridge block along the San Andreas fault in southern California are 0.7–1.6 Ma across a 5–10-km-wide ridge between fault strands (Spotila et al., 1998). Elevations along the ridge are ~1000 m above base level. In this case, where glaciers have not eroded the landscape, oversteepening of the slopes between the fault strands regulated the maximum elevations along the rapidly exhuming narrow ridge (Spotila et al., 1998). If rock uplift on Montague and Hinchinbrook Islands is mostly focused along megathrust fault splays, then the lack of high topography may be partly due to the narrowness of the uplifted region.

**Causes of Rock Uplift and Exhumation**

The AHe age patterns (Fig. 4) clearly indicate that long-term exhumation rates increase to the southwest and are highest at the southwest end of Montague Island. The southwest increase in exhumation rate and magnitude also mimics the southwest increase in the amount of uplift and fault offset in the 1964 earthquake (Plafker, 1967, 1969). There was no measured offset on the Cape Cleare fault onshore after the 1964 earthquake, but seismic data of Liberty et al. (2013) show a 40 m scarp offshore to the southwest. Thus the long-term pattern of exhumation reflects the short-term seismogenic uplift patterns. Given (1) the narrow geometry of Montague and Hinchinbrook Islands; (2) the relatively young thermochronometer ages from samples across the islands that are adjacent to relatively older ages north of the Montague Strait fault; (3) a well-defined topographic expression of faults onshore and their seismic and bathymetric expression offshore; and (4) the correlation between long-term exhumation and coseismic deformation, we infer that exhumation is controlled dominantly by rock uplift along faults. We also infer that Hinchinbrook and Montague Islands have remained the focus of exhumation for at least the past 2–3 m.y., with higher rates to the southwest.

Even though we interpret the majority of exhumation to be on narrow fault-bounded blocks on Montague and Hinchinbrook Islands, we cannot rule out the possibility that rock uplift is spread over a broader region offshore to the southeast. AHe ages on the foothall of the Cape Cleare fault are ca. 6 Ma, indicating late Miocene and younger exhumation, but at a lower long-term rate than rocks on the hanging-wall block. In addition, the shorelines on the Cape Cleare fault foothall and on Middleton Island located ~100 km to the southeast were uplifted in the 1964 earthquake (Plafker, 1969). Thus the exhumation focused along fault splays may be part of broader region of rock uplift caused by underplating along the megathrust. Liberty et al. (2013) reprocessed the TACT deep seismic reflection data and interpreted each of the splay faults to sole into the subduction megathrust separately; they showed a subhorizontal megathrust located 18–20 km beneath Montague Island and a lens-shaped zone of reflections below the megathrust, interpreted as thickening due to underplating and duplexing and coincident with where the Patton Bay, Hanning Bay, and Cape Cleare faults splay off the megathrust (Haeussler et al., 2014). Liberty et al. (2013) inferred that the thickened region causes locking of the megathrust below the western part of Prince William Sound (Zweck et al., 2002), which initiates the splay faults that project to the surface parallel to one another. Underplating and duplexing along the megathrust may also cause broad rock uplift that extends southward and away from the more focused rock uplift and exhumation on Montague and Hinchinbrook Islands. Increased rock cooling starting ca. 2–3 Ma on southern Montague Island is coincident with increased mountain glacial erosion worldwide (Herman et al., 2013) and with the onset of glacial sedimentation in the Saint Elias region (Lagoe et al., 1993; Lagoe and Zellers, 1996; Cowan et al., 2013). Climate cooling and glacier erosion may have enhanced erosion rates on Montague and Hinchinbrook Islands during the Pleistocene, but if glacial erosion was the sole cause of increased rock uplift in southern Prince William Sound, then other parts of Prince William Sound should have had the same rapid uplift during this time. Pavlis et al. (2012) suggested that sediments originally shed from the Saint Elias orogen 2–3 Ma in response to cooling climate and glacial erosion caused duplex stacking and underplating under the Yakataga segment farther to the southeast. Mankemchong et al. (2013) used gravity and magnetic data from the Chugach Mountains north of Prince William Sound to suggest that sediments shed from the Saint Elias Mountains were carried along and underplated above the Yakutat microplate. Thus, the increased volume of subducting sediments starting ca. 2–3 Ma may have also enhanced underplating along the megathrust under southern Prince William Sound, which then increased rock uplift along the megathrust splay faults. We infer that the high rock uplift rate since 2–3 Ma on Montague Island is due mainly to splay faulting and related underplating. Recent glaciation at the surface has accommodated this accelerated exhumation across a narrow region, but has also masked the topographic effects of increased rock uplift.

**CONCLUSIONS**

The thermochronology data from this study provide insight into the style of deformation above the subduction décollement in the Prince William Sound of southern Alaska. Our ages, combined with previously published ages, show that southern Prince William Sound, between the Cape Cleare and Montague Straits faults, is a region of focused exhumation and deformation likely caused by Yukutat flat slab subduction. AHe and AFT ages on Montague and Hinchinbrook Islands are as young as 1.1 and 4.4 Ma, respectively; the youngest ages are at the southwest end of Montague Island. These ages vary across major faults, especially on southwestern Montague Island across the Hanning Bay, Patton Bay, and Cape Cleare faults. Exhumation rates across the Patton Bay fault are ~2 times higher on the hanging-wall block than on the footwall block, leading to as much as 3 km of slip across the Patton Bay fault in the past 3.3 m.y., with decreasing slip to the northeast. The northeast to southwest increase in exhumation rate is coincident with the trend of increasing coseismic uplift from the 1964 earthquake, suggesting that fault-related rock uplift is long lived. Thermochronometer ages are 2–5 times greater north of the Montague Strait fault than to the south, suggesting that this fault is part of a major structural transition that acts as a mechanically strong backstop to deformation, and faster exhumation to the south on Montague and Hinchinbrook Islands. The Montague Strait fault backstop may be a westward mechanical continuation of the Bagley fault system backstop in the Saint Elias orogen, but exhumation is slower in the Montague and Hinchinbrook Islands area, where deformation may be distributed between the Aleutian Trench and southern Prince William Sound.

Splay faulting above the subduction décollement is interpreted as the primary cause for rapid exhumation in southern Prince William Sound. More specifically, rock is being uplifted via
splay faulting that is rooted to the Yakutat–North America plate interface. Underplating at the plate interface in the past ~5 m.y., with increased effects since ca. 3–2 Ma, may be enhancing or driving splay fault formation in southern Prince William Sound. The lack of correlation between exhumation rates or magnitudes and topography suggests that a cooling climate and glacial erosion played a role in limiting topographic growth. Notably, this study shows that splay faults with historic coseismic rupture separated by only a few kilometers can facilitate kilometer-scale exhumation above shallowly subducting plates at million-year time scales.

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REFERENCES CITED


