Extreme Quaternary plate boundary exhumation and strike slip localized along the southern Fairweather fault, Alaska, USA

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ABSTRACT

The Fairweather fault (southeastern Alaska, USA) is Earth’s fastest-slipping intracontinental strike-slip fault, but its long-term role in localizing Yakutat–(Pacific–)North America plate motion is poorly constrained. This plate boundary fault transitions northward from pure strike slip to transpression where it comes onshore and undergoes a <25°, 30-km-long restraining double bend. To the east, apatite (U-Th)/He (AHe) ages indicate that North America exhumation rates increase stepwise from ~0.7 to 1.7 km/m.y. across the bend. In contrast, to the west, AHe age-depth data indicate that extremely rapid 5–10 km/m.y. Yakutat exhumation rates are localized within the bend. Further northwest, Yakutat AHe and zircon (U-Th)/He (ZHe) ages gradually increase from 0.3 to 2.6 Ma over 150 km and depict an interval of extremely rapid >6–8 km/m.y. exhumation rates that increases in age away from the bend. We interpret this migration of rapid, transient exhumation to reflect prolonged advection of the Cenozoic–Cretaceous sedimentary cover of the eastern Yakutat microplate through a stationary restraining bend along the edge of the North America plate. Yakutat cooling ages imply a long-term strike-slip rate (54 ± 6 km/m.y.) that mimics the millennial (53 ± 5 m/k.y.) and decadal (46 mm/yr) rates. Fairweather fault slip can account for all Pacific–North America relative plate motion through Quaternary time and indicates stability of highly localized plate boundary strike slip on a single fault where extreme rock uplift rates are persistently localized within a restraining bend.

INTRODUCTION

Characterizing the evolution of plate boundary faults from earthquakes to orogenesis remains a fundamental challenge for illuminating seismic hazards, placing geodetic deformation into geologic context, and constraining tectonic models across different geologic domains. Plate circuit reconstructions using marine geophysical data provide estimates of relative horizontal plate motions over millions of years (e.g., DeMets and Merkouriev, 2016) but do not resolve vertical motions or how strike slip is localized or distributed along a plate boundary. Though tectonic plates move relatively steadily on geologic time scales, related deformation can occur at various rates and in various styles on either side of transform plate boundaries (Woodcock and Fischer, 1986; Norris and Toy, 2014), which generally widen and become increasingly diffuse within continental interiors (Atwater, 1970). Geodetic and neotectonic studies illuminate patterns and rates of transform plate boundary strain on decadal to millennial time scales (e.g., California, USA: Meade and Hager, 2005; Scharer and Streig, 2019; New Zealand: Norris and Cooper, 2001; Wallace et al., 2007), but whether they accurately portray deformation on million-year time scales commonly remains untested (Sutherland, 1994; Janecke et al., 2011).

The Queen Charlotte–Fairweather transform fault system (British Columbia, Canada, to Alaska, USA) is Earth’s fastest-slipping intracontinental strike-slip fault on decadal to millennial time scales (Fig. 1; Molnar and Dayem, 2010). Dextral slip rates of 50–57 m/k.y. since 12–17 ka are constrained by 184 piercing points along the offshore Queen Charlotte fault (Brothers et al., 2020) and are consistent with estimated rates of 48–53 km/m.y. since 1 ka for the onshore Fairweather fault (Plafker et al., 1978; note mm/yr = m/k.y. = km/m.y.). Similarly, block modeling of GPS data implies decadal slip rates of 46 mm/yr across the Queen Charlotte–Fairweather transform fault system (Elliott and Freymueller, 2020). Decadal to millennial slip on the Queen Charlotte–Fairweather fault system can account for 85%–100% of the 48–53 km/m.y. of Pacific–North America relative plate motion (DeMets and Merkouriev, 2016), suggesting that plate boundary strain is highly localized on these time scales. Here, we test whether this scenario has persisted for the past few million years by reconstructing the space-time evolution of plate boundary exhumation along the southern 170 km of the Fairweather fault.

SETTING

The Queen Charlotte–Fairweather fault system spans ~1150 km as a linear trace and has hosted several M+ strike-slip earthquakes over the past century. The offshore Queen Charlotte fault lies at the boundary between the North America continental and Pacific oceanic plates and is closely aligned with the orientation of plate motion (Fig. 1; ten Brink et al., 2018; Brothers et al., 2020). To the north, the Queen Charlotte and onshore Fairweather faults separate the North America plate from the Yakutat oceanic plateau microplate (Worthington et al., 2012) and become oblique to plate motion. Farther north, localized strike slip on the Fairweather fault transitions to convergence across the St. Elias Mountains (Elliott and Freymueller, 2020), where Oligocene–recent collision of the Yakutat microplate (Plafker et al., 1994) drives rapid thrust-belt exhumation (Enkelmann et al., 2015, 2017). Queen Charlotte–Fairweather fault system morphology changes abruptly at Icy Point, Alaska. A 3 km right step and 30-km-long restraining double bend occur onshore and are as much as 25° oblique to the linear offshore fault trace (Fig. 2; Witter et al., 2018, 2020; Brothers et al., 2020). On the North America plate, topography of the Fairweather Range...
abruptly grows from 600 to 3900 m across the bend. On the Yakutat microplate, ongoing rapid rock uplift within the restraining bend is evident from uplifted late Pleistocene–Holocene marine terraces (Mann, 1986; Witter et al., 2018, 2020) and steeply tilted Miocene–Pleistocene strata (Miller, 1961). Geologic and seismic reflection data (MacKevett et al., 1971; Plafker, 1987) indicate that >4–6 km of structural relief developed across transpressional structures along the eastern Yakutat microplate (Fig. 2B), such as the active Icy Point–Lituya Bay thrust fault (Plafker, 1987; Risley et al., 1992; Elliott and Freymueller, 2020; Fig. 2A).

The Fairweather fault juxtaposes >9-km-thick Paleogene layered gabbro and amphibolite-facies metamorphic rocks on the North America plate against an ~12-km-thick Cretaceous–Cenozoic sedimentary package that overlies the eastern Yakutat microplate (Figs. 2A and 2B; Loney and Himmelberg, 1983; Plafker et al., 1994). The Yakutat sediments include middle Miocene–Pleistocene marine siltstone, sandstone, and conglomerate of the 4-km-thick Topsy and Yakataga Formations (Miller, 1961; MacKevett et al., 1971; Marinovich, 1980; Rau et al., 1983; near sites 1 and 2 in Fig. 2A), which overlie ~8 km of Cretaceous–Paleocene accretionary prism strata (Worthington et al., 2012) and plutons.

**METHODS**

We quantified low-temperature rock cooling histories via (U-Th)/He and fission-track thermochronology of apatite (AHe and AFT, respectively) and zircon (ZHe and ZFT, respectively), with effective closure temperatures of ~60 °C, ~110 °C, ~180 °C, and ~250 °C, respectively (Reiners and Brandon, 2006). We present 33 new ages (22 AHe, 7 ZHe, two AFT, and two ZFT; see the Supplemental Material) and 14 previously published ages (O’Sullivan et al., 1997; McAleer et al., 2009) from 13 Yakutat sites (19 samples) and 12 North America sites (Fig. 2C).

**Figure 1.** Fairweather fault tectonic setting (southeastern Alaska, USA) along the Yakutat—North America plate boundary. Plate velocity is from Elliott and Freymueller (2020). AK—Alaska; Bb—Boundary block; CAN—Canada.

**Figure 2.** (A) Fairweather fault (southeastern Alaska) geology (Wilson et al., 2015). Restraining bend occurs at the onshore transition from strike slip to transpression. (B) Cross section depicting >6 km of structural relief across the eastern Yakutat microplate (MacKevett et al., 1971) and geologic contrast with North America (Loney and Himmelberg, 1983). Fm.—formation. (C) Topography and cooling ages along the Fairweather fault. Thermochronologic systems with effective closure temperatures in parentheses: AHe—apatite (U-Th)/He; AFT—apatite fission-track; ZHe—zircon (U-Th)/He; ZFT—zircon fission-track. Partially reset AFT and non-reset ZHe ages determined for site 1.
We determined the regional exhumation pattern along the southern Fairweather fault from 25 Cretaceous–Paleogene bedrock samples located 20 km southeast to 150 km northwest of Icy Point. We obtained a detailed view of Yakutat exhumation within the restraining bend from an age-depth profile of seven samples from the lower 1.8 km of the Miocene–Pleistocene stratigraphic section at Icy Point. Finally, we illustrate systematic along-strike variations in Yakutat cooling with inverse thermal modeling of individual samples.

RESULTS

On the North America plate, an abrupt northward decrease in AHe ages from 3.4 to 1.2 Ma occurs across the 30-km-long restraining bend (Fig. 3A). The bend separates a ≥20-km-long southern domain of 2.8–3.4 Ma AHe ages (n = 3) from a ≥40-km-long northern domain of 1.2–1.4 Ma AHe ages (n = 5), indicating a step increase in cooling rates from ∼20 to ∼45 °C/m.y. Coincident increases in topography and plate motion obliquity (Fig. 3A) suggest that oblique convergence drives long-term exhumation and topographic growth of the Fairweather Range north of the bend.

On the Yakutat microplate, bedrock AHe (n = 9) and ZHe (n = 8) ages increase gradually from 0.3 to 2.6 Ma over a distance of 150 km to the northwest of Icy Point (Fig. 3B). This pattern is consistent with AFT ages of 0.7–2.4 Ma (n = 3), whereas older ZFT ages of 3.2–27.5 Ma (n = 4; Fig. 2C) place an upper limit on Quaternary bedrock cooling (<250 °C). Focused Yakutat exhumation within the restraining bend is suggested by an abrupt increase in exhumation magnitudes across the bend (from reset AHe to ZHe ages), followed by consistent exhumation magnitudes northwestward along strike (Fig. 2C).

The AHe age-depth profile suggests an onset of rapid Yakutat cooling within the restraining bend at Icy Point at 0.4 ± 0.1 Ma (Fig. 3C). A break in age-depth profile slope occurs at stratigraphic depths of 2.3–2.9 km and AHe ages of 0.3–0.5 Ma, indicative of a transition to rapid rock uplift and erosion that has unroofed as much as 3.8 km of Miocene–Pleistocene strata. This exhumation magnitude is consistent with partially to non-reset ZHe and AFT ages that preclude greater post–0.4 Ma exhumation at this site. Unroofing of 2–3.8 km of strata since 0.4 Ma requires an exhumation rate of ∼10 km/m.y. adjacent to the offshore Fairweather fault (base of section) and 5 km/m.y. adjacent to the offshore Icy Point–Lituya Bay thrust fault.

A punctuated interval of extremely rapid Yakutat cooling northwest of Icy Point is indicated by paired AHe and ZHe ages that differ by only 0–0.6 m.y. (n = 6; Fig. 3B). Inverse thermal modeling indicates a period of extreme >200 °C/m.y. cooling rates at progressively younger times closer to the restraining bend. Rapid cooling is ongoing within the bend at Icy Point, where exposed rocks have been exhumed from ∼90 °C and Miocene–Pleistocene strata continue to be tilted and unroofed (Fig. 4B, site 1e). In contrast, to the northwest outside the bend where Cretaceous–Paleogene bedrock were exhumed from >160 °C, initially rapid cooling has since transitioned to more moderate cooling of <50 °C/m.y. (Fig. 4B, sites 7, 11). Average north-west-to-southeast Yakutat exhumation migration rates of 55 ± 5 km/m.y. (ZHe) and 53 ± 5 km/m.y. (AHe) are estimated from cooling age–distance gradients since 2.6 Ma (Fig. 3B). This cooling trend likely continued northward, as suggested by an early Pliocene pulse of rapid cooling in the northern Boundary block (Fig. 1;
Schartman et al., 2019), before being overprinted by recent collision-zone exhumation.

DISCUSSION

Thermochronometric data reveal the space-time pattern and rates of Quaternary exhumation along the Yakutat–North America transform plate boundary (Fig. 4A). Yakutat rock uplift rates within the restraining bend at Icy Point are among the fastest in the world, with unroofing rates of as much as 10 km/m.y. and cooling rates >200 °C/m.y., characterizing rapid exhumation since 0.4 Ma (Figs. 3C and 4B). Similarly rapid Yakutat cooling rates occurred in the past at sites along the fault to the northwest. We estimate geothermal gradients of ∼25–30 °C/km on the basis of thermochronometric data and independently estimated stratigraphic (Fig. 3C) or structural depths (Fig. 2B), consistent with the modern 30 ± 6 °C/km geothermal gradient nearby (Risley et al., 1992; Batir et al., 2013). Hence, the Yakutat cooling rates suggest >6–8 km/m.y. exhumation rates, which match both Pleistocene unroofing rates and Holocene terrace uplift rates of ∼6–8 m/k.y. within the restraining bend (Witter et al., 2018). In contrast, much slower ∼0.7–1.7 km/m.y. North America exhumation rates and an absence of uplifted terraces occur east of the bend (Fig. 4A). Abrupt increases in North America topography, obliquity, and exhumation rate across the restraining bend (Fig. 3A) suggest a stable Quaternary configuration of oblique convergence and moderate exhumation without significant bend migration. North of the restraining bend, both Yakutat and North America exhumation rates remain <2 km/m.y. along the transform plate boundary (Fig. 4A) until the St. Elias Mountains collision zone (Fig. 1), where extreme >5 km/m.y. exhumation rates occur (McAleer et al., 2009; Enkelmann et al., 2015, 2017; Schartman et al., 2019).

Evidence at million-year, millennial, and decadal time scales suggests a consistent spatial pattern of rapid Yakutat deformation localized within the restraining bend along the transform plate boundary. Fairweather fault deformation abruptly changes from pure strike slip to transpression at the restraining bend, forming a positive flower structure (Fig. 2; Woodcock and Fischer, 1986; Plafker, 1987). Here, greater rates of rock exhumation, terrace uplift, and geodetic shortening occur on the west side of the plate boundary, indicating that extremely rapid Yakutat deformation rates are localized within the bend (Fig. 4A).

The zone of eastern Yakutat transpression increases to 12 km in width and >6 km in structural relief within 32 km to the northwest of Icy Point (Fig. 2B). The thick North America gabbro and gneiss located just north of Icy Point may form a stable upper crustal backstop to the restraining bend that focuses deformation and efficient erosion of the weaker Cretaceous–Cenozoic Yakutat sedimentary cover to the south (Fig. 2). This strong contrast in near-surface rock strength across the plate boundary may also explain the higher North America topography, underlain by crystalline rock, despite 3 × 4 × faster Yakutat exhumation rates.

Diverse data suggest that the Fairweather fault has remained Earth’s fastest-slipping intracontinental strike-slip fault throughout the Quaternary. We interpret the thermochronometric pattern of rapid, transient exhumation to reflect prolonged translation of the eastern Yakutat microplate through a stationary restraining bend along the edge of the North America plate (Fig. 4C). Thus, the horizontal migration of rocks that preserve the zone of rapid exhumation represents a time-averaged strike-slip rate of 54 ± 6 km/m.y. since ca. 2.6 Ma (Fig. 3B). The new million-year slip rate estimate is similar to shorter-time-scale millennial rates of 53 ± 5 m/k.y. (Plafker et al., 1978; Brothers et al., 2020) and decadal rates of 46 mm/yr (Elliott and Freymueller, 2020). In addition, a consistent ∼6:1 ratio of horizontal to vertical deformation within the restraining bend occurs over wide-ranging time scales, including million-year strike-slip to maximum exhumation rates (this study), millennial strike-slip to terrace uplift rates (Witter et al., 2018; Brothers et al., 2020), geodetic strike-slip to fault-normal rates (Elliott and Freymueller, 2020), and coseismic maximum horizontal to vertical offsets (Tocher, 1960).

The consistent deformation patterns and 46–54 mm/yr strike-slip rates on decadal, millennial, and million-year time scales imply that highly localized strike slip on the southern Fairweather fault can account for 85%–100% of the 48–53 mm/yr of Pacific–North America relative plate motions (DeMets and Mercouliev, 2016) throughout the Quaternary. Along the length of the Pacific–North America transform boundary, this simple and localized behavior of the southern Fairweather strike-slip fault in Alaska is in stark contrast with more complex and distributed behavior across an ∼100-km-wide zone of strike-slip faults in California (USA), despite similar overall rates and kinematics of relative plate motions (DeMets and Mercouliev, 2016; ten Brink et al., 2018). The southern Fairweather fault end member of transform plate boundary localization may have initiated before ca. 20 Ma via heating of the eastern Yakutat microplate by nascent Pacific
lithosphere and, once established, been maintained by rheological contrasts (ten Brink et al., 2018). Decoupling of upper crustal deformation from deeper plate interactions at the restraining bend is suggested by the Yakutat vertical juxtaposition of weak, rapidly deforming sediments overlying strong oceanic plateau lithosphere. In general, we document that restraining bends along transform plate boundaries can generate exhumation rates as extreme as those observed in collisional orogenic zones, but may be more cryptic in the geologic record because exhumed rocks are quickly advected out of zones of focused transpression. Our work bridges time scales of deformation along the active Fairweather fault and reveals the persistence of such intense transform plate boundary strain localization over millions of years.

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