Rapid exhumation of ice-covered rocks of the Chugach–St. Elias orogen, Southeast Alaska

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ABSTRACT

Ongoing oblique collision and flat-slab subduction of the Yakutat terrane has produced Earth's highest coastal mountain range, the Chugach–St. Elias orogen in Southeast Alaska. Massive glaciers and ice fields cause extensive erosion, but also limit access to rocks that allow detailed study of the orogen. Fission track and U/Pb dating of detrital zircon from glacial rivers reveal the exhumation history of the Chugach–St. Elias orogen. Orogenic development started ca. 30 Ma and pulses of exhumation occurred 20 ± 2 Ma and 11 ± 2 Ma. Differential exhumation occurred across major fault zones and the locus of exhumation shifted southward. The ca. 5 Ma cooling ages of detrital zircon in the Pliocene–Pleistocene Yakataga Formation reveal that source rock exhumation was likely associated with faulting along the ice-covered Fairweather fault–Contact fault system.

INTRODUCTION

The Chugach–St. Elias orogen has been formed by the ongoing oblique collision of the Yakutat terrane with North America (Fig. 1). The high latitude, high relief, and maritime climate result in intense glaciation that is well expressed in the ~200-km-long and ~10-km-wide Bagley ice field–Seward Glacier system that covers most of the orogenic divide (Figs. 1 and 2). With more than 50% ice cover, this orogen is unique on the planet because erosion by warm-based glaciers undoubtedly plays a dominant role in exhumation. Our understanding of the long-term exhumation history (>10^6 yr) using low-temperature thermochronometers is challenged by thick ice cover that restricts sampling to the remote mountain ridges that tower over the massive glaciers. However, the glaciers act as conveyor belts, and they transport material exhumed below the glaciers to the flanks of the orogen. Our strategy is to examine sediments from glacial rivers for insights into how exhumation has proceeded beneath the otherwise inaccessible ice cover.

This study provides the first insight into the exhumation history of the Chugach–St. Elias orogen as it is recorded by detrital zircon fission track and U/Pb ages. Our results differ significantly from bedrock studies and reflect the disparity of cooling ages exposed in valleys (glacial river) and ridges (bedrock).

GEOLOGICAL SETTING

Alaska consists of a complex of far-traveled terranes amalgamated to North America, mostly since the Mesozoic (Fig. 2). In southern Alaska, major units include the Paleozoic–Mesozoic Wrangellia terrane separated by the Border Range fault from the Mesozoic Chugach terrane, which was metamorphosed and intruded by the Sanak-Baranof plutonic belt during Eocene ridge subduction (Plafker et al., 1994; Sisson et al., 2003). The Contact fault separates the Chugach terrane from the younger Paleocene–early Eocene Prince William terrane, and was reactivated during Chugach–St. Elias orogenic development (Bruhn et al., 2004). Outboard and to the south is the actively colliding Yakutat terrane.

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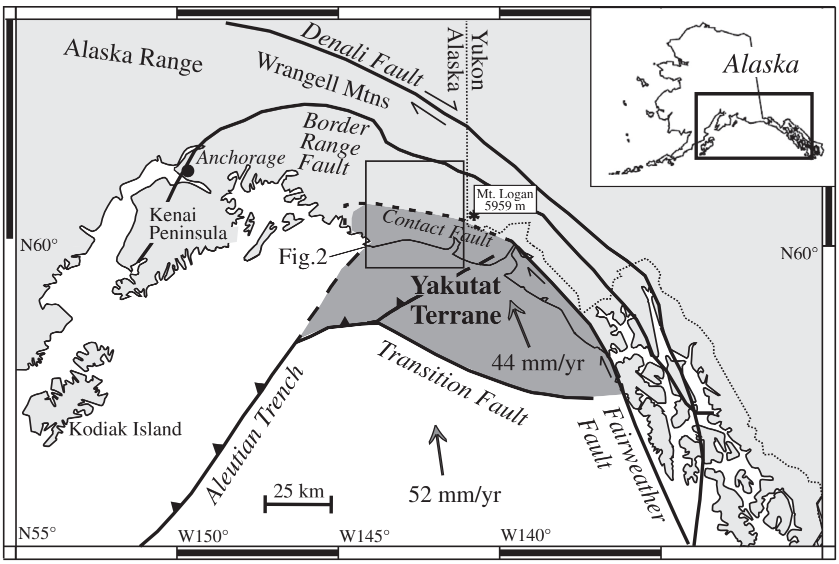

Figure 1. Tectonic map of Southeast Alaska. Plate motion vectors are from Fletcher and Freymueller (1999).

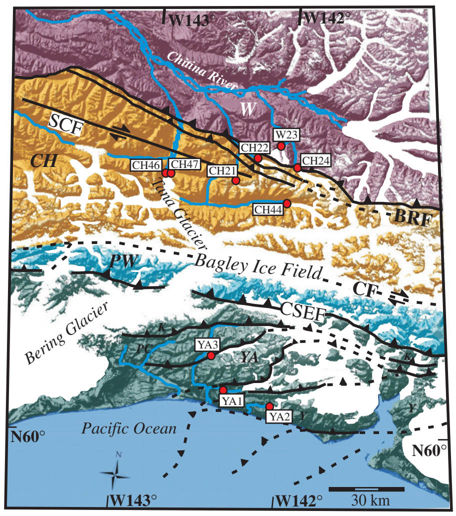

Figure 2. Geological map of study area with sample locations and major geological units. W—Wrangellia terrane (purple), CH—Chugach terrane (yellow), PW—Prince William terrane (blue), Yakutat terrane (green) with K—Kultieth Formation, PC—Poul Creek Formation, Y—Yakataga Formation. Faults and assumed faults are solid and dashed lines. BRF—Border Range fault, SCF—Steward Creek fault, CF—Contact fault, CSEF—Chugach–St. Elias fault.

The Fairweather dextral transform bounds the Yakutat terrane to the east (Fig. 1). This transform is inferred to have formed ca. 30 Ma and has allowed northward transfer of the Yakutat terrane. The leading edge of the more continental part of the Yakutat terrane encountered the Aleutian trench between 10 and 5 Ma and has since collided obliquely (Fig. 1; Plafker et al., 1994). Most of the Tertiary sedimentary cover to the Yakutat terrane has been scraped off basement rocks and accreted to the growing fold-and-thrust belt. Imbricate cover rocks include the lower Eocene–Oligocene Kultieth Formation, the upper Eocene–upper Miocene Poul Creek Formation, and the fluvial and glacial marine Yakataga Formation that was deposited in response to orogenic growth since ca. 6–5 Ma (Lagoe et al., 1993; Plafker et al., 1994).

METHODS

Ten samples were collected from rivers that drain glaciers that erode and obscure rocks of the Wrangellia and Chugach terrane north of the Bagley Ice field and the cover of the Yakutat terrane to the south (Fig. 2; Table 1). Zircon fission track analyses are described in the GSA Data Repository.[1] Grain-age distributions were deconvolved into component age populations using binomial peak fitting (Table 1; Fig. DR1; Brandon, 1992). The U/Pb ages of individual zircon grains yielding the youngest fission track ages were measured using laser ablation inductively coupled plasma–mass spectrometry at the University of Arizona (Fig. 3; see the Data Repository).

[1]GSA Data Repository item 2008234, zircon fission track and U/Pb data, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

RESULTS

Double Dating

An emerging analytical approach is the double dating of zircon grains to establish a more complete picture and unique insight into the history of single grains (i.e., Reiners et al., 2005). A key issue from our analysis is that many of the detrital zircon grains from areas underlain by Mesozoic–Eocene rocks have very young fission track ages (younger than 15 Ma; closure temperature, T_C = 240 ± 40 °C; Brandon et al., 1998). Double dating (zircon fission track and U/Pb) can help resolve whether the zircon fission track cooling ages reflect exhumation of older rocks or whether they represent young shallow intrusive or volcanic rocks.

This latter option is important because Neogene intrusive bodies and volcanic layers occur throughout the study area, but most are of unknown age (see Plafker et al., 1994). These young igneous rocks could be potential sources of zircons that record igneous ages and not exhumation. To address this possibility we double dated the youngest zircon fission track grains of YA1, YA2, CH44, and CH46. Almost every grain (96%) we dated has much older U/Pb ages (Fig. 3), indicating that the zircon fission track ages are cooling ages likely related to exhumation. In general, the majority of all U/Pb ages are 70–50 Ma, similar to the time of ridge subduction that formed the Chugach metamorphic complex and the plutonic rocks of the Sanak-Baranof belt (Sisson et al., 2003).

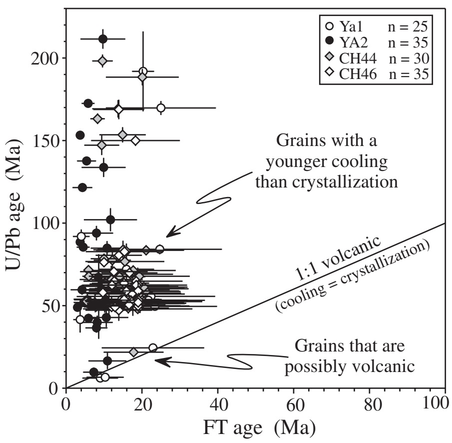

Figure 3. Zircon fission track (FT) ages versus U/Pb age for individual detrital zircon grains. Error bars are 2σ.

TABLE 1. DETRITAL ZIRCON FISSION TRACK RESULTS

Sample	Longitude (°N), Latitude (°W)	n	Age range (Ma)	P1	P2	P3	P4	P5	P6	P7
Wrangellia terrane										
WR23	60°55.544	60	50–197						92.1 ± 11	119 ± 15
	141°58.933								47.5%	52.5%
Border Range fault zone–Chugach terrane										
CH22	60°53.342	60	17–110				30.4 ± 3.9	42.1 ± 3.5	82.8 ± 24	
	142°11.651						28%	65.7%	6.3%	
CH24	60°53.307	60	22–206				32.9 ± 3.8		77.2 ± 8.2	102 ± 18
	141°54.411						10.2%		56.5%	33.3%
Chugach terrane										
CH21	60°48.816	105	11–107		13.1 ± 2.2		28.2 ± 3.5	42.0 ± 2.0		
	142°18.893				3.8%		20%	76.2%		
CH44	60°44.263	104	5–61		8.2 ± 2.3	21.5 ± 1.9		34.5 ± 2.6		
	141°57.200				5.1%	47.5%		47.3%		
CH46	60°50.294	103	9–53		13.5 ± 2.2	21.7 ± 1.0		35.6 ± 6 5.9%		
	142°46.981				9.4%	84.7%				
CH47	60°50.127	105	8–51		10.7 ± 2.2	17.4 ± 1.8	27.1 ± 1.8	35.2 ± 2.5		
	142°44.742				3.6%	12.2%	49.3%	34.9%		
Yakutat terrane										
YA1	60°07.366	105	3–123	6.3 ± 0.9		17.9 ± 1.1		37.3 ± 1.6	81.8 ± 5.8	
(Y, PC)	142°21.042			4.3%		16.5%		62%	17.2%	
YA2	60°04.330	105	3–112	5.2 ± 0.6	10.7 ± 0.7		24.8 ± 1.3		60 ± 4.5	
(Y)	142°08.212			12.3%	31.7%		39.8%		16.2%	
YA3	60°13.202	107	9–136		9.9 ± 2.6		25.1 ± 1.5	40.8 ± 2.2	62.2 ± 6.6	121.7 ± 11
(K., PC, Y)	142°31.945				1.7%		21%	54.7%	15.5%	7.1%
Comparison Yakataga Formation with Chugach terrane				P1′	P2′	P3′	P4′	P5′		
YA2′ without grains that comprise the oldest peak		88		5.2 ± 0.6	10.6 ± 0.7	21.0 ± 2.6	26.8 ± 2.6			
				15%	37%	16%	32%			
Chugach terrane (CH21, 44, 46, 47)		417			12.4 ± 1.4	20.0 ± 1.5	27.5 ± 1.5	40.6 ± 1.7		
					6%	25%	38%	31%		

Note: n = total number of analyzed grains; P = best fitted age populations (in Ma) with 1σ confidence interval, calculated using BINOMFIT 1.1 of Brandon (1992). The relative size of the age population is given in percent. Age range indicates the youngest and oldest single grain ages. Drainage area composition: Y—Yakataga Formation, PC—Poul Creek Formation, K—Kultieth Formation; ζ = 382.5 ± 9.9 yr cm^2.

Detrital Zircon Fission Track Dating

Zircon fission track results of samples from areas underlain by the Wrangellia and Chugach terranes (north) have age populations that are younger to the south with major changes in age populations across the Border Range fault. Samples CH21, CH44, CH46, and CH47 yield age populations from 42 to 8 Ma (Table 1), but farther north in the Chugach terrane (CH22, CH24) populations range from 102 to 30 Ma, and north of the Border Range fault they are 120–90 Ma (W23). Therefore significant vertical displacement along the Border Range fault is likely, as indicated by the difference in the ages north of the fault (W23) and south of it (CH22, CH24). This result suggests that Wrangellia formed the backstop for the exhumation of the Chugach terrane starting ca. 30 Ma, which coincides with subduction of Yakutat lithosphere (Plafker, 1987). The oldest age population typical of the Chugach terrane (P5 in Table 1) is 42–35 Ma, which records cooling after Eocene ridge subduction and metamorphism (Sisson et al., 2003).

Three samples were taken from drainages underlain entirely by the Yakutat terrane (Fig. 2). The drainage area of YA1 is underlain by the Yakataga and Poul Creek Formations, YA2 is underlain by the Yakataga Formation, and YA3 is underlain by the Poul Creek and Kultieth Formations and the Yakataga Formation. Bedrock samples from the Poul Creek and Kultieth Formations (Perry, 2006; Meigs et al., 2008) yielded zircon fission track results similar to YA1 and YA3, which are from drainages mostly underlain by these formations (Table 1). In contrast, zircon fission track ages from the Yakataga Formation vary significantly from different locations (Perry, 2006), and differ from our results for samples YA1 and YA2, which show young age populations not detected by the bedrock samples. In general, the zircon fission track age populations are slightly older than the suspected stratigraphic age of the strata in the drainage area (e.g., Lagoe et al., 1993; Plafker et al., 1994). However, samples derived from the Yakataga Formation yield a young grain age population (P1: 5.2 and 6.3 Ma) similar to the age of the base of the Yakataga Formation (5.6 Ma; Lagoe et al., 1993). Because the depositional age of the Yakataga strata in our study area is poorly known (ca. 5.6 Ma and younger), zircons of P1 can be interpreted as either partially reset fission track ages, or as cooling ages recording a fast exhuming source at the time of deposition. Zircon with high radiation damage has a lower closure temperature and anneals at lower temperatures (Garver et al., 2005). The U/Pb dating of the youngest zircon fission track age (P1 of YA1 and YA2) shows that the crystallization ages are relatively young (170–42 Ma) and U concentrations range from 60 to 1300 ppm (Table DR1). Because there is no correlation between the young fission track ages and the amount of radiation damage accumulation, we interpret P1 as cooling ages. This interpretation is supported by vitrinite reflectance studies that indicate that heating of the Yakutat sedimentary cover in this area did not exceed ~160 °C (see Perry, 2006), well below the temperature needed to reset zircons with this level of damage (Garver et al., 2005).

DISCUSSION

Yakataga Formation

Because the drainage area of YA2 is underlain exclusively by rocks of the Yakataga Formation, we use this sample to capture cooling of the Chugach terrane, which supplied much or most of the detritus to this particular unit (Perry, 2006). An important aspect of this analysis is to determine the cooling age distribution of the Chugach terrane, which originally supplied the bulk of detritus to the Yakataga Formation. To get a qualitative understanding of the cooling signal that can be attributed to the Chugach terrane, we took the component age distribution, and removed the older grain ages attributed to recycling from the adjacent and underlying Poul Creek and Kultieth Formations (P6 = 60 Ma). We then recalculated the component populations (P′ in Table 1) with the residual grains that likely represent sediments shed off the Chugach terrane. It is reassuring that the age populations P2′, P3′, and P4′ of YA2 are in agreement with the component populations of the combined Chugach terrane samples (P′; Table 1). This finding suggests that rocks of the Chugach metamorphic complex were the main source (~70%) for the Yakataga Formation; this is supported by petrological studies (Perry, 2006).

The youngest age population in YA2 (5.2 ± 0.6 Ma) is the youngest set of zircon fission track cooling ages so far recognized in the orogen. As such they deserve special consideration, because they must have been derived from Chugach terrane rocks cooled during the latest and most dramatic phase of orogenesis. Considering the northwestward plate motion of the colliding Yakutat terrane (Fig. 1), we suggest that these rapidly exhuming rocks were shed from an area located ~50–200 km east, under the eastern Bagley ice field–Seward Glacier system, in what is now the central and eastern St. Elias Range. Today this elongated glacier system covers the transition from the Fairweather fault to the Contact fault and coincides with the highest topography of the mountain range (Fig. 1). The fact that such fast-cooled zircon grains are not identified in our samples of the Chugach terrane, or by bedrock samples north or south of it, supports the suggestion that the most rapidly exhumed rocks are located under the ice and farther east.

Exhumation of the Chugach–St. Elias Orogen

These new data support a new exhumation model for the Chugach–St. Elias orogen (Fig. 4). This system started ca. 30 Ma, a time that coincides with the formation of the

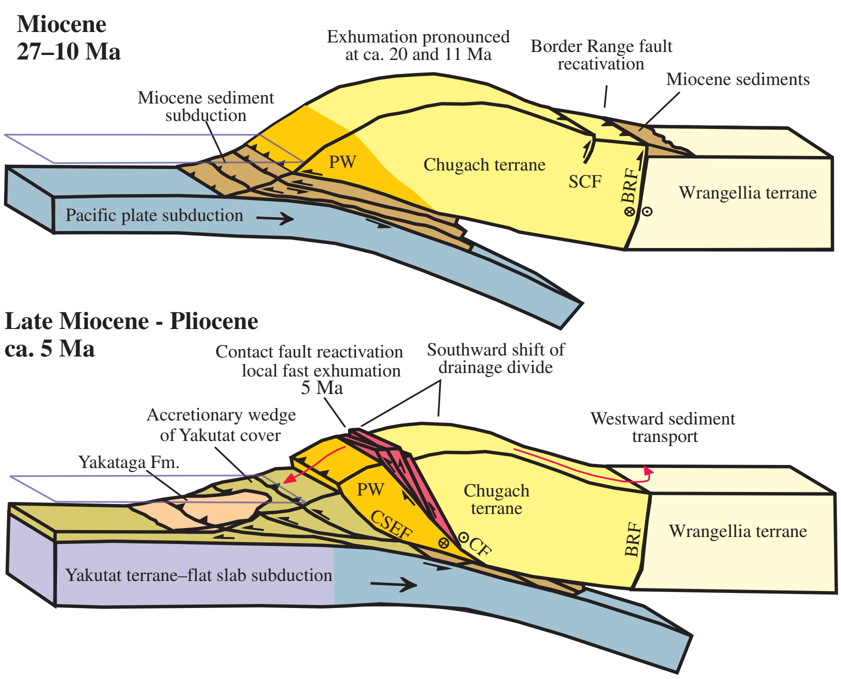

Figure 4. Exhumation model for the Chugach–St. Elias orogen. PW—Prince William terrane, CSEF—Chugach–St. Elias fault, CF—Contact fault, SCF—Stewart Creek fault, BRF—Border Range fault.

Fairweather fault and initiation of subduction and arc volcanism in the Wrangell Mountains (Plafker et al., 1994). In this model the reactivated Border Range fault forms the backstop for the first phase of exhumation of the Chugach–Prince William terrane. Two exhumation phases at 20 ± 2 Ma and 11 ± 2 Ma followed, as revealed by P2 and P3 of the Chugach samples, suggesting that the center of the exhumation was located south of the eastward projection of the Stewart Creek fault (Figs. 2 and 4; Pavlis et al., 2003). These two phases of Chugach terrane exhumation coincide with changes in the Pacific plate motion relative to North America ca. 20 and ca. 10 Ma (Stock and Molnar, 1988), and the transition of oceanic plate subduction to flat slab subduction of the Yakutat terrane ca. 10 Ma (e.g., Eberhart-Phillips et al., 2006).

The latest and most dramatic exhumation started ca. 6–5 Ma and was driven by the final collision of the Yakutat terrane, and resulted in glacial marine sedimentation of the Yakataga Formation. For this to occur, the backstop must have shifted southward and the Contact fault was reactivated as the westward continuation of the Fairweather fault. We suspect that dextral transpression is associated with lens-like pop-up structures, resulting in locally very rapid exhumation (Fig. 4). The likelihood that the Yakataga Formation was mainly fed by the Chugach terrane indicates that by this time the drainage divide was located farther north, allowing transport of sediments south into the synorogenic basin. Therefore, development of the Bagley ice field–Seward Glacier system may be a consequence of the faulting activity along the Contact fault and is therefore younger than 5 Ma.

Comparison with Bedrock Studies

The bedrock thermochronological data sets from within the core of the orogenic belt (Chugach) and in the frontal deformation (fold and thrust of the Yakutat cover rocks) are difficult to compare directly with the detrital data, but the best approach is to look at the overall spatial and temporal distribution of exhumation rates. In the Chugach bedrock samples, apatite U-Th/He and apatite fission track ages give relatively slow exhumation rates that range between ~0.1–0.3 mm/yr that are applicable mainly between 10 and 25 Ma and only to rocks in the interfluves without ice cover (see Berger et al., 2008; Meigs et al., 2008). Our young zircon fission track ages from the Chugach, which are mainly between 8 and 11 Ma, would indicate exhumation of 0.5–1.5 mm/yr in the fast-exhuming parts of the orogen under the ice cover of the Bagley ice field (see Brandon et al., 1998). In the frontal part of the orogenic belt, i.e., the active fold-and-thrust belt that involves cover to the Yakutat terrane, exhumation rates of exposed rock are 1.5–4.0 mm/yr in the past 2 m.y. (apatite U-Th/He dating; Berger et al., 2008). The key issue in our finding is that relatively rapid exhumation has occurred in the spine of the orogenic belt, which is ice covered and cut by the Contact fault. It is likely that the source of the young exhumed rocks revealed by the detrital zircon fission track analysis is local slivers of fault-bound rocks brought up along the Contact fault, and glacial erosion may have driven faulting and rapid exhumation, but details of this process await further investigation.

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