Transport of the Yakutat Terrane, Southern Alaska: Evidence from Sediment Petrology and Detrital Zircon Fission-Track and U/Pb Double Dating

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ABSTRACT

Two hypotheses have been offered to account for the transport and accretion history of the Yakutat terrane in southern Alaska. To investigate these two options, we deconvolved fission-track (FT) and U/Pb ages of detrital zircons from stratigraphically coordinated samples collected in the northern Robinson Mountains into component populations. The strata of the Yakutat terrane include the Middle Eocene Kulthieth Formation, the Lower Oligocene to Lower Miocene Poul Creek Formation, and the Miocene-Pleistocene Yakataga Formation. The Kulthieth and Poul Creek formations record erosion of a simple, uniform, long-lived, nonvolcanic source terrain that crystallized from ~50 to 220 Ma and cooled from ~40 to 110 Ma. Miocene cooling episodes recorded in the source to the Kulthieth and Poul Creek formations are likely associated with plutons in the northern Coast Plutonic Complex and the Kuiu-Etoilin belt. The Upper Miocene to Pleistocene Yakataga Formation records erosion of rocks that crystallized from ~50 to 53 Ma and cooled below the zircon FT closure at ~70–20 Ma. Upper Miocene strata are likely derived from erosion of the Chugach–Prince William terranes and the superimposed Sanak-Baranof plutonic belt. The uniform provenance of the Kulthieth and Poul Creek formations, the overall FT grain age distribution, and the distinct lack of volcanic zircons favor a northern position of the Yakutat terrane since the Eocene. However, a far-traveled southern option for the basement rocks cannot be ruled out, but it is unlikely that the Eocene and younger cover strata were deposited far to the south.

Introduction

Southern Alaska has been the site of the collision of a number of far-traveled allochthonous terranes during the Cenozoic (Plafker 1987; Plafker et al. 1994). One of these, the Yakutat terrane, is currently attached to the Pacific plate and is being underthrust beneath the Chugach terrane at rates of ~0.56 mm/yr (Fletcher and Freymueller 1999; Veenstra et al. 2006). This terrane was transported northwestward, parallel to the Alaskan continental margin (fig. 1).

Two hypotheses have been offered to account for the Yakutat terrane's transport history from ~50 Ma to the present (cf. Bruns 1983; Plafker 1987). The first, here termed the northern option or the short-transport hypothesis, involves transport over a relatively short distance (~600 km) from a northern position, with sedimentary cover strata being derived from local sources. This hypothesis invokes modest Neogene transport and significant shortening within the terrane boundary (Plafker et al. 1994). The second, here termed the southern option or the long-transport hypothesis, involves transport from a faraway southern position. This hypothesis is based on the reconstruction of magnetic anomalies and the development of the subduction of the Kula-Farallon spreading center (Bruns 1983). The southern option places the basement rocks of the Yakutat terrane as far south as northern California or southern Oregon in the Eocene (~45 Ma; cf. Bruns 1983; Plafker et al. 1994) and thus involves ~1500–2000 km of northward transport along the Cordilleran margin. The sedimentary cover rocks would consequently reflect movement along the western edge of the northern Cordillera (see Cowan et al. 1997).

The transport and accretion history of a terrane can be addressed by provenance analysis (i.e., Garver and Brandon 1994*b*; Cowan et al. 1997).

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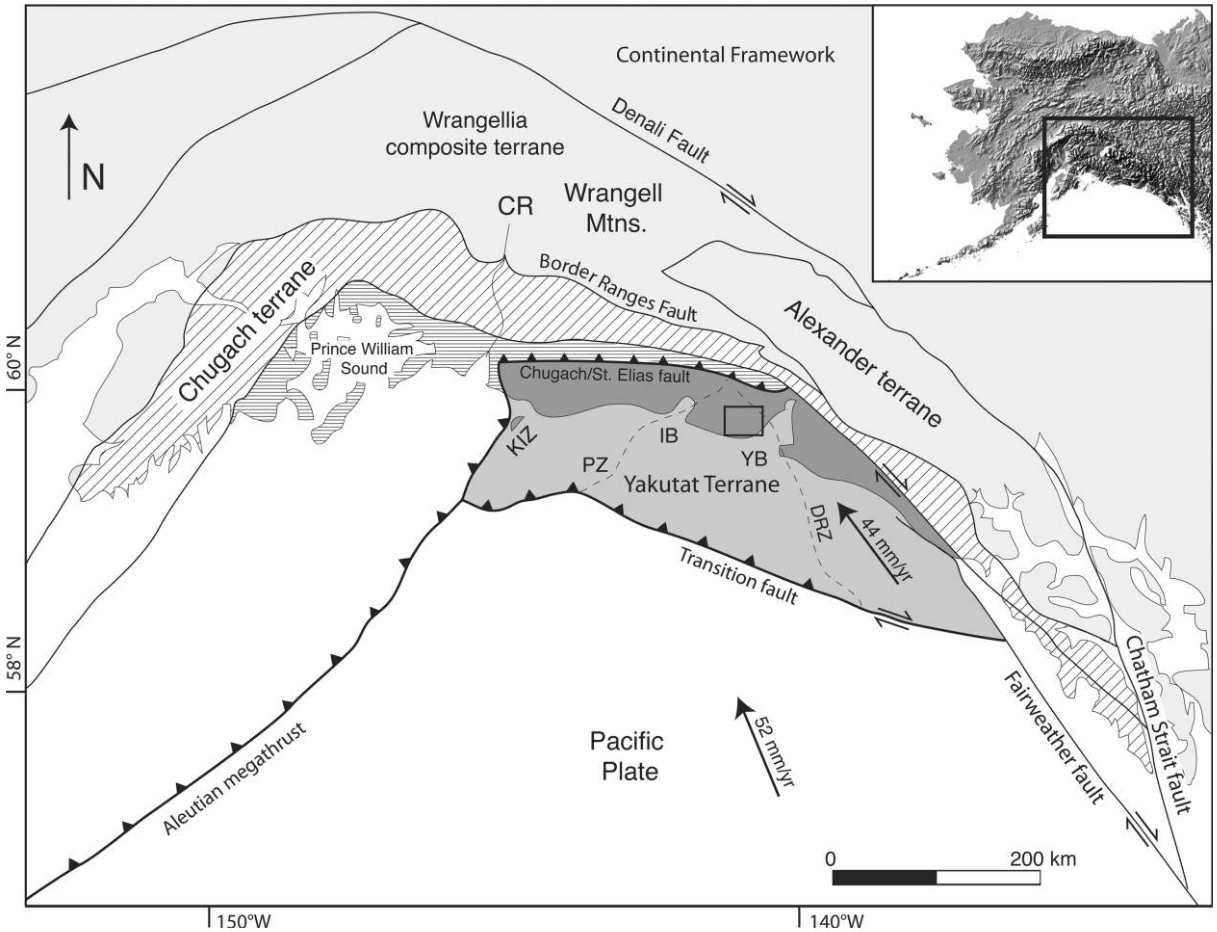


Figure 1. Geologic map of southern Alaska showing major accreted terranes and fault systems, including the Yakutat terrane (modified after Plafker 1987; Plafker et al. 1994). Recent plate velocities between the Pacific plate and the Yakutat terrane are based on GPS measurements reported by Fletcher and Freymueller (1999). *CR*, Copper River; *DRZ*, Dangerous River Zone; *IB*, Icy Bay; *KIZ*, Kayak Island Zone; *PZ*, Pamplona Zone; *YB*, Yakutat Bay. The black rectangle indicates the location of this study.

By resolving the provenance of the sedimentary cover of the Yakutat terrane, we can identify different source areas and its transport history can be reconstructed. The sedimentary cover strata of the Yakutat terrane are well suited for zircon analysis, but so far few detrital zircon fission-track (DZFT) studies have been conducted (Armstrong 1988; Plafker et al. 1992; Johnston 2005; Meigs et al. 2008) and virtually no detrital zircon U/Pb analyses have been done on these rocks (see Gehrels et al. 1995; Haeussler et al. 2006).

In contrast, a number of studies have characterized the various plutonic and volcanic rocks of the northern Cordillera from the southwestern coast of Oregon and Washington to the Chugach/St. Elias Range in southern/southeastern Alaska (Anderson 1988; Garver and Brandon 1994*a*, 1994*b*; Bradley et al. 2003; Himmelberg et al. 2004). The most tectonically significant element of the continental margin is the Coast Plutonic Complex (CPC) that extends from northwestern Washington into southeastern Alaska (Armstrong 1988). Intrusion and exhumation of this complex have been dated from ~80 to 45 Ma (Harrison et al. 1979; Parrish 1983; Armstrong 1988; Armstrong and Ward 1991; Stowell and Crawford 2000). The CPC plays a key role in the reconstruction of Yakutat terrane transport history because in either a long- or a short-transport hypothesis, the CPC must have been a source to the Yakutat cover sequence.

In this study, 13 sandstones from the sedimentary cover of the Yakutat terrane were analyzed for their petrography. Then detrital zircons from these sandstones were analyzed by fission track (FT) to obtain cooling ages, followed by U/Pb dating of each of the same grains to determine its crystallization age (fig. 2). This double-dating distinguishes between zircons derived from volcanic sources (where single grains have identical FT and U/Pb ages) and those derived from plutonic and metamorphic sources (Carter and Moss 1999; Carter and Bristow 2003). Afterward, vitrinite reflectance on isolated kerogen was analyzed for four samples to establish the maximum postdepositional temperature range. The analytical data presented here are interpreted in relation to stratigraphic age and significance for transport of the Yakutat terrane.

Regional Geological Setting

The Yakutat terrane is approximately 600 km long and 200 km wide. Its transport and collision have resulted in the transition of the Queen Charlotte–Fairweather transcurrent fault in the east to the Alaska-Aleutian subduction zone in the west. Geophysical, seismic, and structural studies show that the Yakutat terrane arrived at its present position along the southern Alaska margin since the Pliocene (Bruns 1983; Fletcher and Freymueller 1999, 2003). GPS measurements of plate velocity for the Yakutat microplate indicate current plate motion of ~44 mm/yr to the north (Plafker et al. 1994; Fletcher and Freymueller 1999, 2003), a rate slightly slower than Pacific plate motion of ~52 mm/yr in the region (Sauber et al. 1997; Fletcher and Freymueller 1999, 2003).

Successive accretion of the Chugach–Prince William (CPW) composite terrane to the north of the Yakutat terrane occurred from Late Cretaceous to early Tertiary time (Plafker 1987; Plafker et al. 1994). It is inferred that the Chugach terrane was accreted before the Prince William terrane and formed a backstop for collision of outboard terranes (Plafker et al. 1994). Rocks of the Chugach terrane are locally metamorphosed up to amphibolite facies, and this metamorphism is inferred to be the result of a northwestward shift in Kula plate motion and/or the subduction of the Kula-Farallon spreading center beneath the accreted terrane from the Late Paleocene to the Middle Miocene (Engebretson et al. 1985; Plafker 1987; Lonsdale 1988; Stock and Molnar 1988; Atwater and Stock 1998). Subduction of this spreading center resulted in the intrusion of dikes and plutons at ~65–50 Ma, and these form the time-trangressive Sanak-Baranof plutonic belt (Plafker et al. 1994; Bradley et al. 2003; Trop and Ridgway 2007).

Underthrusting of ~225 km of the Yakutat terrane beneath the Chugach terrane has resulted in the formation of the Chugach/St. Elias Range. This collision forced dramatic surface uplift and ero-

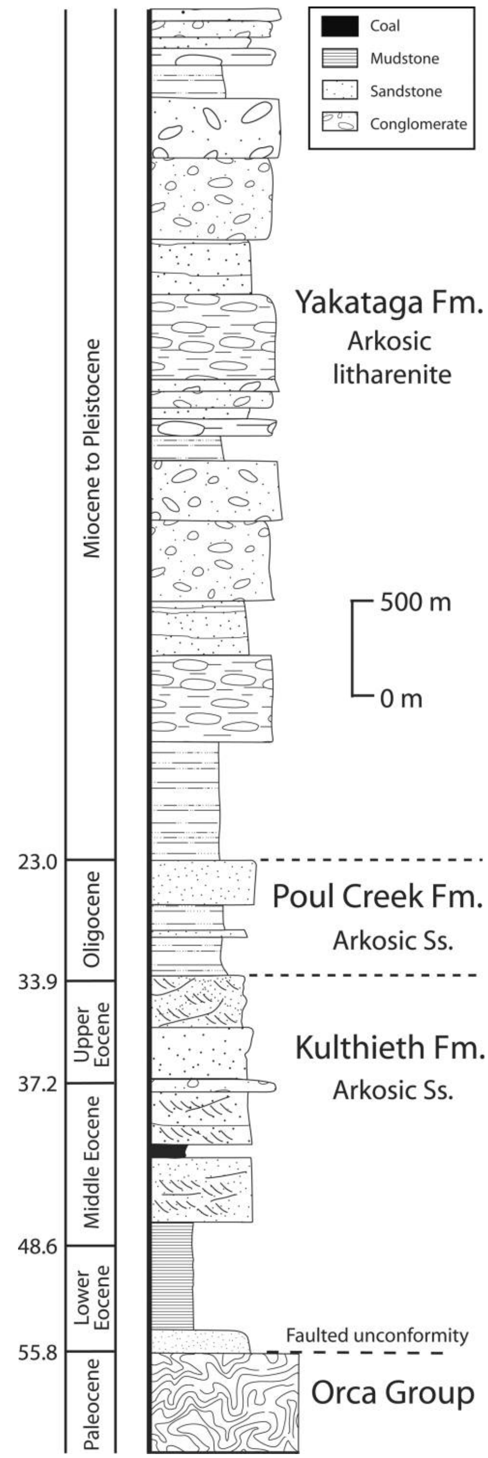


Figure 2. Stratigraphic column of the Tertiary sequence of the Yakutat terrane from the northern Robinson Mountains of southern Alaska. Sample numbers and locations are recorded with petrologic facies determined by point count analyses of multiple thin sections analyzed from each formation. Age determinations of units are based on Plafker's (1987, 1992) flora and faunal assemblages.

sional exhumation (Plafker 1987; Meigs and Sauber 2000; Montgomery 2002; Spotila et al. 2004; Berger and Spotila 2008; Berger et al. 2008).

Stratigraphy of the Yakutat Terrane

The stratigraphy of the Yakutat terrane records sedimentation since the Eocene (Plafker 1987). The sedimentary cover is underlain by two types of basement: (1) poorly studied ~50–55-Ma basaltic oceanic plateau rocks to the west and (2) continental margin rocks of the Upper Paleocene and Lower to Middle Eocene Orca Group to the east, including metamorphosed rocks of the Chugach terrane (Plafker 1987). The basement units are separated by the inactive Dangerous River Zone (fig. 1), a north-south-striking high-angle reverse fault (Plafker 1987; Bruhn et al. 2004) that marks an internal transition from metamorphosed Chugach continental crust to oceanic plateau. Stratigraphic sequences vary in facies and thicknesses across this boundary, but only strata west of the DRZ are analyzed and discussed in this article.

In the eastern part of our study area, the Yakutat cover strata rest unconformably on the Orca Group, part of the CPW terrane (Plafker et al. 1994). Lying unconformably on the Orca Group are three formations that include the Middle Eocene Kulthieth Formation (~55.8–33.9 Ma), the Lower Oligocene to Lower Miocene Poul Creek Formation (~33.9–23.0 Ma), and the Miocene to Pleistocene Yakataga Formation (~23.0 Ma to Present; fig. 2; Plafker 1987). Age estimates are based on Gradstein et al. (2004).

Kulthieth Formation. The Kulthieth Formation consists mainly of organic-rich sandstones that unconformably overlie the Orca Group in the northern Robinson Mountains. This unit consists of arkosic sandstone with interbedded medium- to thick-bedded coal seams and abundant marine fossils (Plafker 1987). Biostratigraphic ages of the fossil assemblages suggest deposition during the Early Eocene to the Early Oligocene (~54–33 Ma) in nonmarine alluvial-plain, delta-plain, barrier-beach, and shallow-marine settings (Plafker 1987).

Sandstones contain abundant cross-bedding, showing sediment transport to the northwest (Plafker 1987; Bruhn et al. 2004). The estimated thickness of the Kulthieth Formation in the Yakataga area is ~2.8 km (Miller 1957, 1971; Plafker 1987; Wahrhaftig et al. 1994), but the depositional age range for this formation is not well constrained.

Poul Creek Formation. The Poul Creek Formation conformably overlies the Kulthieth Formation and consists of highly deformed, fine-grained, glauconitic, organic-rich sandstones interbedded with water-lain basaltic tuff, breccia, pillow lava, and related deposits of the intertonguing Cenotaph Volcanics (Plafker 1987). The Poul Creek Formation records a marine transgression and has an estimated thickness of ~1.9 km (Plafker et al. 1980; Plafker 1987). Age constraints for this unit are better than those for the Kulthieth Formation, ranging from Upper Eocene to Lower Oligocene and possibly into the Lower Miocene (~40–20 Ma; Plafker 1987). DZFT data with young grain-age populations of ~24 to ~29 Ma help constrain depositional age (Johnston 2005). The nonmarine Cenotaph Volcanics and marine Topsy Formation to the east are believed to be post–Lower Oligocene to pre–Middle Miocene in age and range in thickness from ~0.5 to 1.5 km (MacKevett et al. 1971).

Yakataga Formation. The Miocene to Plio-Pleistocene Yakataga Formation overlies the Poul Creek Formation and consists mainly of glacially derived sediment with abundant marine strata containing dropstones and diamictites. The unit thickens from east to west and locally reaches ~6 km total (Bruns and Schwab 1983; Plafker 1987). The formation is generally divided into an upper and a lower unit. Deposition of the lower unit occurred in neritic to bathyal water depths (Plafker 1987; Martin 1993). The upper unit is recognized by its transition into thick diamictite characterized by dropstones in bioturbated sandstones inferred to have been derived from the Chugach and St. Elias mountains (Eyles and Lagoe 1990; Lagoe et al. 1993; Martin 1993; Lagoe and Zellers 1996; White et al. 1997). Deposition of the Yakataga Formation apparently records the onset of late Cenozoic glaciation and includes the development of high-latitude ice sheets in the Northern Hemisphere at ~5–6 Ma (Kennett 1986; Eyles and Lagoe 1990). Depositional age constraints, which are poor, are based on benthic foraminifera and molluscan fauna and range from Miocene to Plio-Pleistocene (Plafker 1987; Eyles and Lagoe 1990).

Methods

Thirteen sandstone samples were analyzed with FT and U/Pb double dating of single zircons. For DZFT analysis, zircon aliquots of each sample were mounted in Teflon and polished to expose internal crystal surfaces etched in a NaOH-KOH eutectic melt (see Bernet and Garver 2005). The resulting composite probability distribution was deconvolved into component peak ages for each sample, and then all samples from each of the three formations were combined (figs. 3, 4; Brandon and Vance 1992; Brandon 1996; see details in Perry 2006).

U-Pb analysis on two samples from each of the three formations was done with a Micromass IsoProbe multicollector inductively coupled mass spectrometer (ICPMS) with a laser ablation system at the University of Arizona, Tucson. For each sample all FT-dated grains were dated by U/Pb

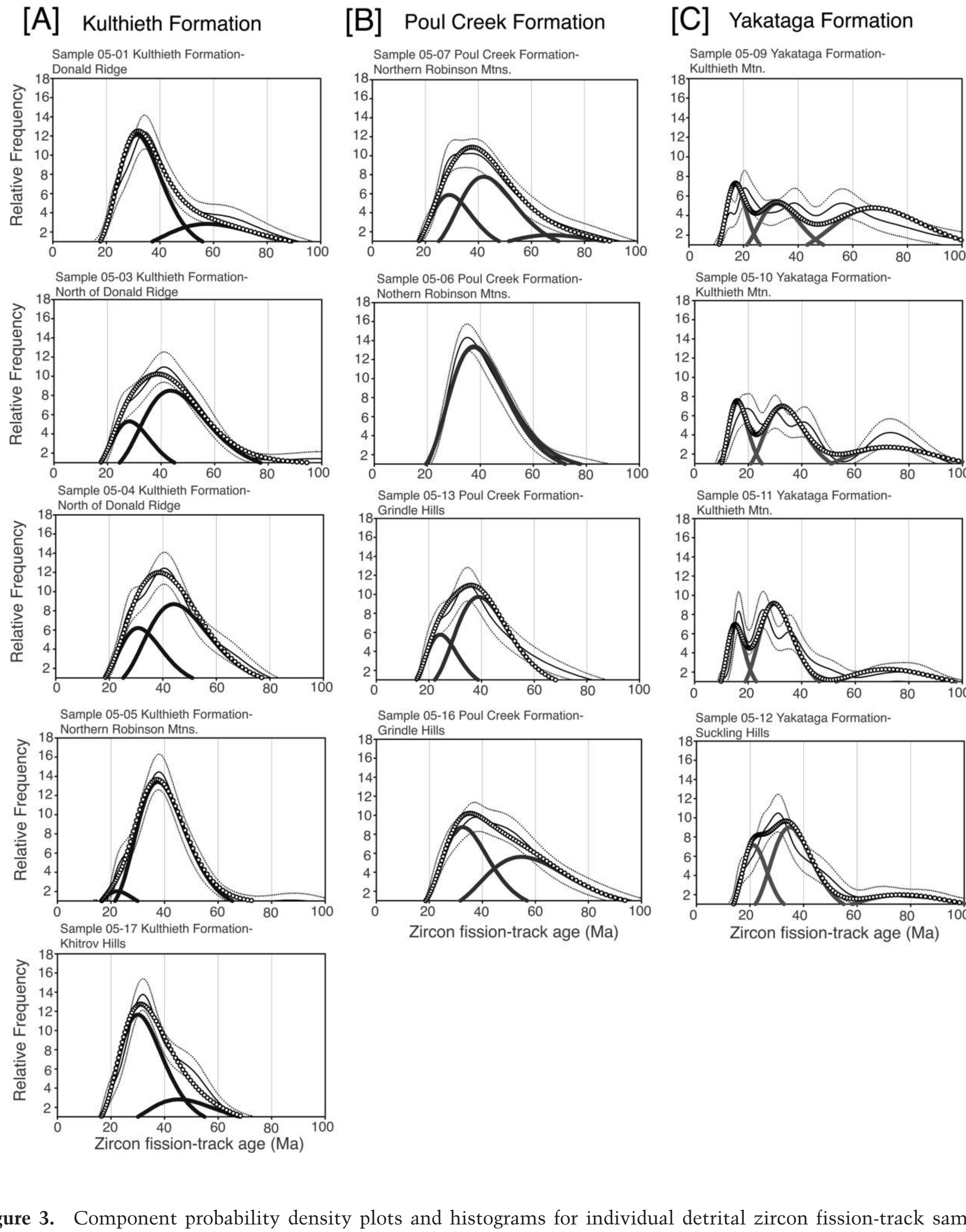


Figure 3. Component probability density plots and histograms for individual detrital zircon fission-track samples analyzed. *A*, Kulthieth Formation; *B*, Poul Creek Formation; *C*, Yakataga Formation.

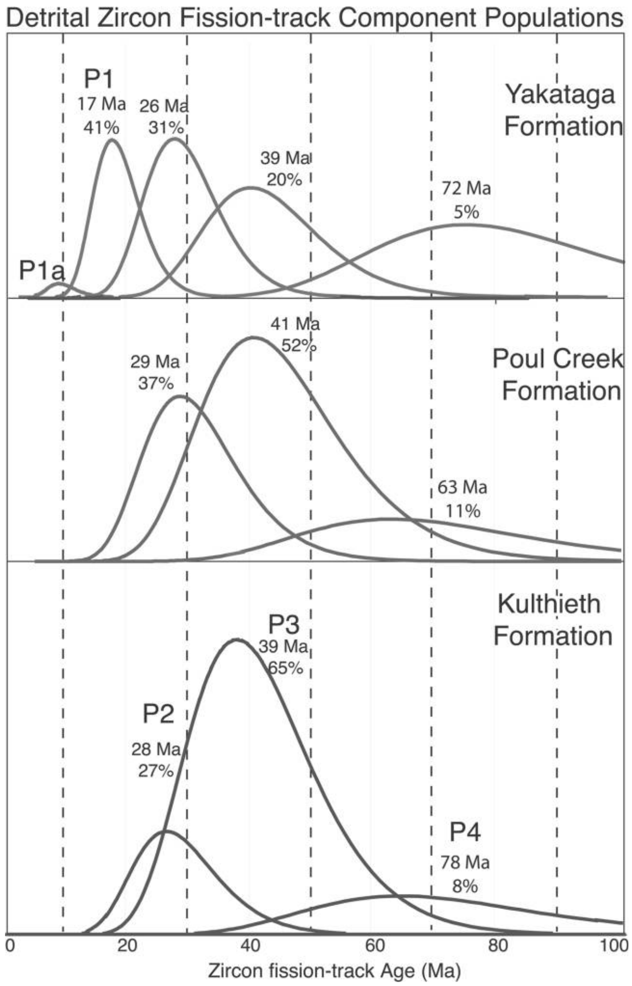


Figure 4. Combined component probability density plot and histogram for single-grain detrital zircon fission-track ages from the Yakutat terrane. The Yakataga Formation records a younger peak-age population (~17–20 Ma).

analysis (~650 double-dated grains); then an additional 50 randomly selected grains from the formation were analyzed (150 grains per formation total; fig. 5).

Standard sedimentary petrologic analysis was done on thin sections of all DZFT-dated samples. Samples were stained for Ca and K for feldspar identification, and 200-grain points were counted in all thin sections (see Perry 2006). For $\%R_o$, whole-rock samples (for samples 05-01, 05-03, 05-04, and 05-07) were sent to Humble Geochemical Services for analysis of isolated kerogen. Samples were selected based a young DZFT cooling age and analyzed at Humble Geochemical Services for hydrocarbon potential yield, color alteration, thermal alteration index, palynofacies, and vitrinite reflectance.

DZFT Analysis

All samples yielded pooled DZFT ages ranging from 25.1 (+0.9/ − 1.0) to 39.4 Ma (+1.7/ − 1.8; table 1; figs. 3, 4). All but one sample failed χ^2, which indicates considerable age dispersion and reflects source heterogeneity (Bernet and Garver 2005). The observed grain-age distributions were deconvolved into main component age populations using the binomial peak-fitting technique (see Brandon 1996).

All samples have a significant primary population (P_1) ranging in age from 29.8 (+3.0/ − 3.3) to 57.6 Ma (+13.5/ − 17.6). One sample from the Poul Creek Formation passed χ^2 but still has two resolvable component populations (see table 1). The Kulthieth, Poul Creek, and Yakataga formations record three primary component populations ($P_2 \sim 30$–39 Ma, $P_3 \sim 42$–45 Ma, and $P_4 \sim 57$–97 Ma) that are nearly identical. The dominate component population (>50% of the grain age distribution) throughout the Yakutat stratigraphy ranges from ~30 to 39 Ma (P_2). A significant difference is the occurrence of a younger (~15–24 Ma) component population in the Yakataga Formation.

U/Pb Analysis

Kulthieth Formation. The same grains dated with DZFT analysis in samples 05-01 and 05-04 were analyzed using the laser-ablation ICPMS U/Pb dating technique (fig. 5; fig. 6*A*, 6*B*). In addition, 50 random grains were analyzed from sample 05-01, resulting in 150 total analyses for the Kulthieth Formation. Three U/Pb crystallization age populations of ~59, ~94, and ~159 Ma and a single age of ~1788 Ma were determined. All highly discordant ages (<5%) due to Pb loss or high common Pb content were excluded from the concordia diagrams (Stacey and Kramers 1975; fig. 5).

Comparing the DZFT single-grain cooling ages for the young Miocene component population (~30 Ma) with their associated U/Pb single-grain crystallization ages, one notes that no single grain has identical cooling and crystallization ages (fig. 6*A*, 6*B*). Zircons belonging to the ~30-Ma DZFT component population have U/Pb crystallization ages mainly between ~50 and 60 Ma, but the full range is ~50–420 Ma (fig. 6*A*).

Poul Creek Formation. A total of 150 grains from the Poul Creek Formation were analyzed, including 100 DZFT-dated grains from samples 05-07 and 05-13 and 50 randomly selected grains from sample 05-13 (fig. 5). Four crystallization age peaks were detected: ~59, ~71, ~94, and ~147 Ma, while three grains yielded ages of ~318, ~365, and ~1865 Ma.

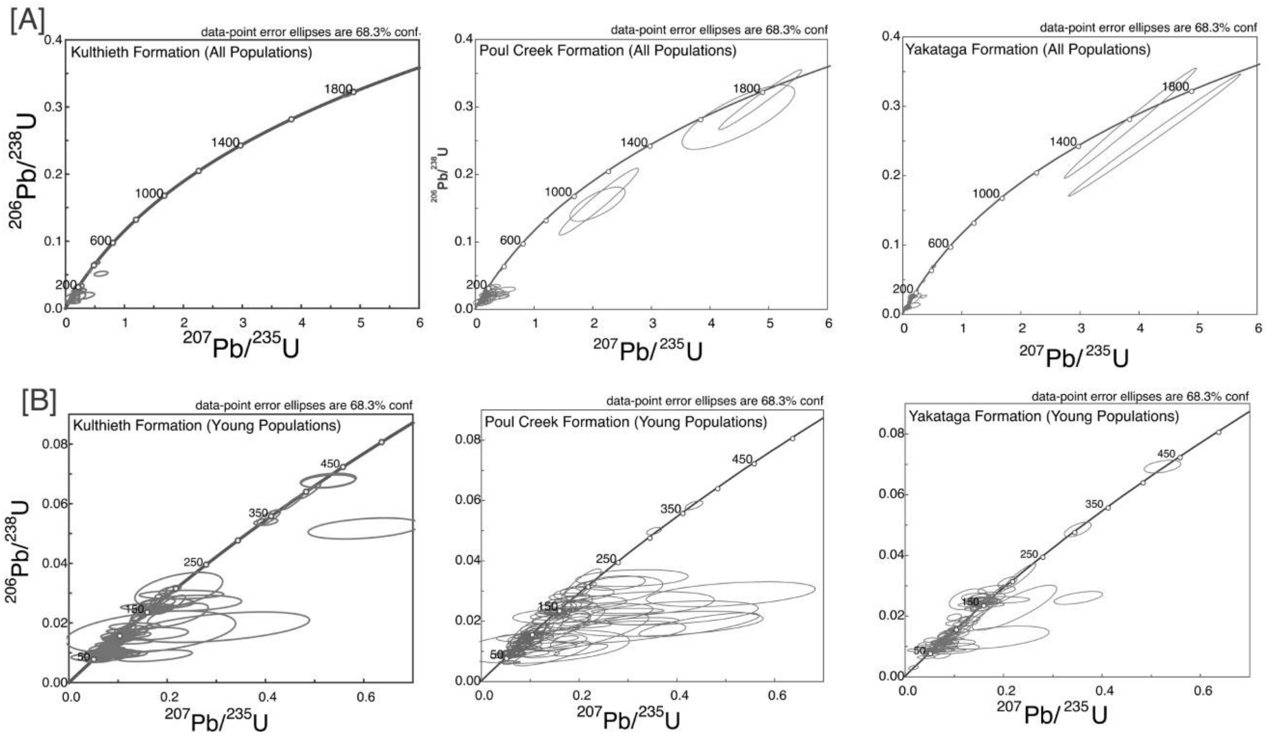


Figure 5. U/Pb concordia diagrams for all samples analyzed. *A*, Concordia diagrams recording ages ranging from ~0 to 2000 Ma. *B*, Younger populations determined in all samples analyzed from ~0 to 500 Ma.

All highly discordant ages (<5%) due to Pb loss or high common Pb content were excluded from the concordia diagrams (fig. 5). Comparing zircons of the ~40-Ma or younger DZFT cooling age population with their associated U/Pb crystallization ages, we see that the majority of these grains have U/Pb ages of ~50–85 Ma and no single grain has FT and U/Pb ages that are identical (fig. 6*C*, 6*D*).

Yakataga Formation. A total of 150 zircon grains were analyzed for the Yakataga Formation: 100 FT-dated grains from samples 05-10 and 05-11, plus 50 additional randomly selected grains from sample 05-11 (fig. 5). Analyses were normalized, and data were plotted on both concordia diagrams and histogram plots (fig. 5). Three main crystallization age populations were determined: ~52, ~71, and ~155 Ma.

A comparison of the DZFT-determined cooling ages with the U/Pb crystallization ages for each grain analyzed may be found in Perry (2006). All highly discordant ages due to Pb loss or high common Pb content were excluded from the concordia diagrams. As expected, the DZFT single-grain cooling ages are younger than their associated U/Pb ages, which range from ~50 to 200 Ma (fig. 6*F*). Only one grain in the ~20–40-Ma DZFT group has a cooling age and a crystallization age identical or within error of each other. If we isolate the ~20-Ma-dated component population and compare the equivalent U/Pb crystallization ages, we see that the ~20-Ma DZFT cooling age population has a range of U/Pb crystallization ages of ~50–200 Ma, with the majority of the grains (80%–85%) representing a population with a crystallization age of 50–55 Ma (fig. 6*E*).

Comparison of Analytical Techniques

The possibility exists that FT sample preparation and grain selection for FT analysis may bias selection of grains that were double dated. To investigate the degree of a potential grain selection bias, we dated an additional 50 randomly selected grains for each stratigraphic unit (150 grains total). The grain age comparison (double-dated grains vs. randomly selected grains) shows that for all late Paleozoic and younger grains, the distributions are virtually identical (fig. 7). Consequently, we are confident that no significant bias has been introduced by our analytical approach to double dating.

However, if we look at the small percentage of grains of Devonian age and older, we see some differences in the results between the double-dated and randomly selected grains. For the FT-selected

Table 1. Summary of Component Populations for Individual Samples of the Yakutat Terrane

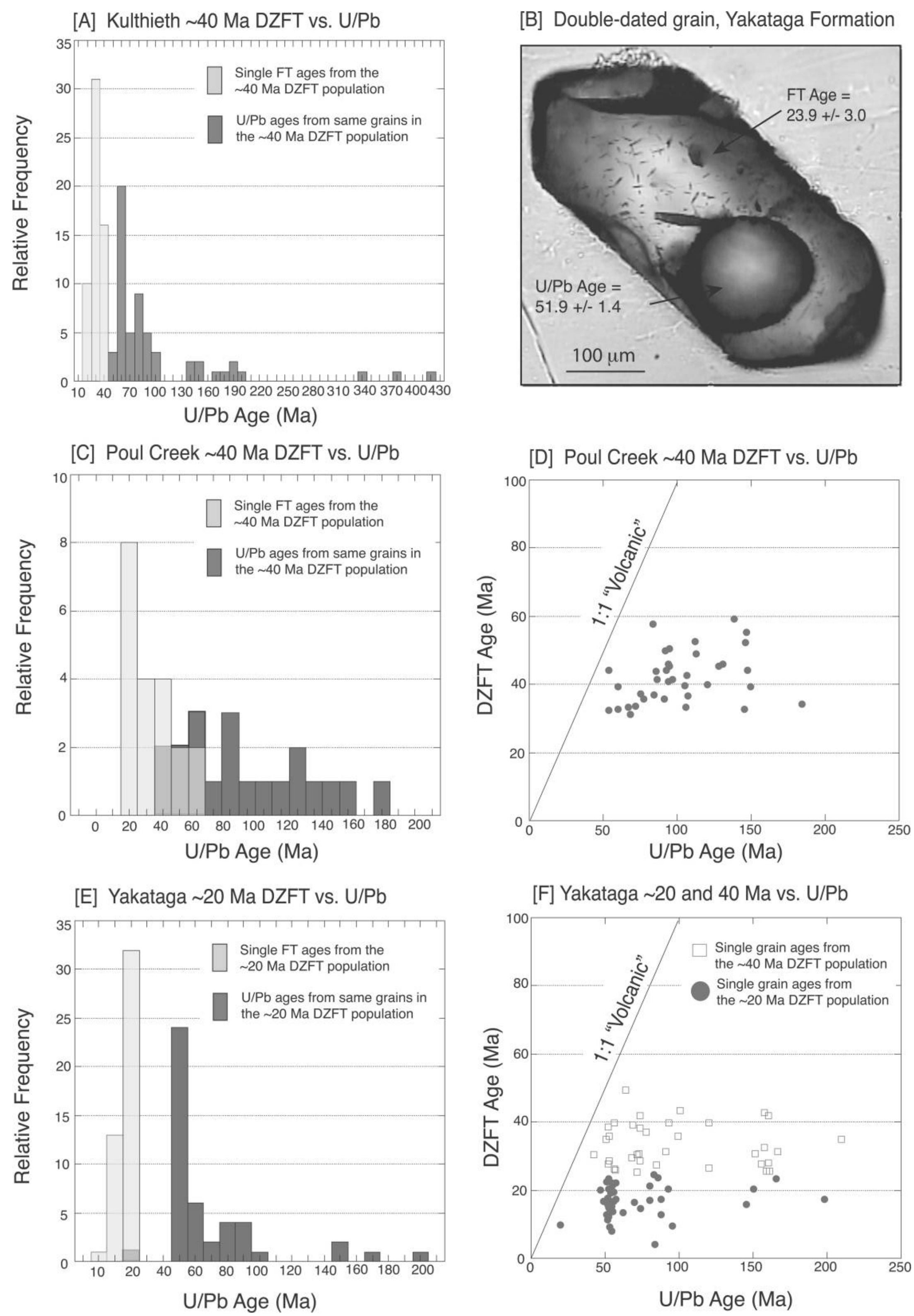
		Gaussian component population ages			
Sample	n_I	P_1	P_2	P_3	P_4
Yakataga Formation (Miocene-Pleistocene):					
05-09	50	16.9 −1.8/+2.1 $\pi_f = 39.3\%$	32.4 −4.9/+5.7 $\pi_f = 30.2\%$	…	67.8 −8.4/+9.6 $\pi_f = 30.4\%$
05-10	50	15.8 −1.7/+1.9 $\pi_f = 43.5\%$	32.8 −4.1/+4.7 $\pi_f = 39.4\%$	…	72.5 −11.6/+13.7 $\pi_f = 17.1\%$
05-11	50	15.1 −1.6/+1.8 $\pi_f = 37.4\%$	29.8 −3.0/+3.3 $\pi_f = 48.8\%$	…	71.9 −12.6/+15.3 $\pi_f = 13.7\%$
05-12	50	21.3 −3.0/+3.4 $\pi_f = 38.7\%$	34.8 −4.6/+5.3 $\pi_f = 49.4\%$	…	76.8 −16.2/+20.5 $\pi_f = 11.9\%$
Poul Creek Formation (Upper Eocene–Upper Miocene):					
05-07	50	…	29.0 −5.8/+7.3 $\pi_f = 39.2\%$	42.0 −9.9/+13.0 $\pi_f = 49.8\%$	67.2 −21.6/+31.7 $\pi_f = 11.0\%$
05-08	50	…	37.5 −3.7/+4.1 $\pi_f = 96.0\%$	…	65.8 −32.7/+64.8 $\pi_f = 4.0\%$
05-13	50	24.4 −4.1/+4.9 $\pi_f = 35.8\%$	38.9 −4.9/+5.6 $\pi_f = 64.2\%$	…	…
05-16	50	…	32.6 −4.5/+5.3 $\pi_f = 58.6\%$	…	54.7 −10.2/+12.6 $\pi_f = 41.4\%$
Kulthieth Formation (Lower Eocene–Lower Oligocene):					
05-01	50	…	31.4 −3.0/+3.3 $\pi_f = 78.4\%$	…	57.6 −13.5/+17.6 $\pi_f = 21.6\%$
05-03	50	…	28.1 −4.7/+5.7 $\pi_f = 34.2\%$	43.5 −6.0/+7.0 $\pi_f = 59.2\%$	97.0 −28.9/+41.1 $\pi_f = 6.6\%$
05-04	50	…	30.8 −6.0/+7.4 $\pi_f = 41.1\%$	44.1 −6.8/+8.0 $\pi_f = 58.9\%$	…
05-06	50	22.3 −5.1/+6.6 $\pi_f = 12.6\%$	37.5 −3.6/+4.0 $\pi_f = 82.2\%$	…	80.2 −25.5/+37.3 $\pi_f = 5.2\%$
05-17	50	…	30.1 −3.4/+3.9 $\pi_f = 79.8\%$	45.3 −11.5/+15.3 $\pi_f = 20.2\%$	…

Note. Samples 05-09 and 05-06 had only one mount. n_I, total number of grains analyzed; π_f, proportion of grains that compose the peak.

grains, 2.3% of the grains had U/Pb ages that were Devonian or older, and for the randomly selected laser-ablated grains, 4% were Devonian or older. Although slightly different, we can conclude that the potential bias against older grains introduced by the FT selection process is not significant. We do note, however, that the random laser-ablated grains did capture the oldest grains. Five of the six randomly selected old grains were of Precambrian age, but in the FT-selected grains, only two of seven old grains were Precambrian (the U/Pb age range for all of these old Precambrian grains is 933–1950 Ma). This finding applies only to this data set, and we would expect that in other studies the FT selection process may remove a significant fraction of old grains with very high radiation damage and very high track densities. Therefore, while the observed differences do not affect the overall conclusions of this study, they are worth considering for future work that utilizes FT and U/Pb double dating of single zircons.

Interpretation

Kulthieth and Poul Creek Formations. Sandstones of the Kulthieth and Poul Creek formations are rich in K-feldspar and quartz and are virtually identical in terms of their sedimentary petrography (see Perry 2006), DZFT ages, and U/Pb ages of detrital zircon. A key finding is that the DZFT and U/Pb age populations in the two formations are almost identical. The Paleocene to Cretaceous DZFT population range is ~58–96 Ma in the Kulthieth Formation and ~55–67 Ma in the Poul Creek



Formation. The Eocene DZFT population, which comprises about 50% of all grains analyzed, ranges from ~38 to 45 Ma in the Kulthieth Formation and from ~33 to 42 Ma in the Poul Creek Formation (table 1). U/Pb age populations for the grains that make up the Eocene DZFT age population in both the Kulthieth and the Poul Creek formations are ~59, ~71, ~94, and ~147–159 Ma. The similarity in both cooling age populations and crystallization age populations implies a long-lived source terrane that provided sediment with uniform characteristics and shed >50% of the zircons analyzed onto the Yakutat terrane in the Eocene to Early Miocene.

The Miocene DZFT population in the Kulthieth and Poul Creek formations shows much greater variation, ranging from ~22–31 Ma in the Kulthieth Formation (12%–80% of the grains) to ~24–29 Ma in the Poul Creek Formation (36%–40% of the grains). These peaks are generally similar in age in each unit, but the percentage varies widely from 18% to 80%. Therefore, these populations are generally minor and variable in the percentage of zircon grains that represent them.

Although variable, the Miocene DZFT ages represent an important proxy for the depositional age of the two formations, provided that these young ages represent source rock cooling and not postdepositional resetting. This is an important caveat because a tongue of the Cenotaph Volcanics occurs in the Poul Creek Formation to the west (but not in the study area), and its thermal history needs to be carefully considered.

Our best clue to the thermal history of these strata comes from vitrinite reflectance studies, which generally show that units in the study area remained below temperatures required for DZFT annealing. Based on vitrinite reflectance analysis, it is unlikely that temperatures were in excess of ~160°C for both the Kulthieth and the Poul Creek Formations. Vitrinite reflectance values throughout the northern Robinson Mountains suggest thermal maturity for the Kulthieth Formation, ranging from $\%R_o = 0.37\%$ to 3.41%, corresponding to a wide apparent temperature range of ~44–275°C (Johnsson et al. 1992; Johnsson and Howell 1996). However, vitrinite reflectance on three samples used for both DZFT and U/Pb analysis yield much lower values for in situ organic material of $\%R_o = 0.49\%$–0.80% (~40°–160°C; Johnsson and Howell 1996; see details in Perry 2006). So, for the samples dated, the vitrinite reflectance indicates that the sandstones in the study area did not experience heating high enough to reset the zircon FT system, even partially (see Garver et al. 2005).

For the Poul Creek Formation, the Miocene cooling ages (~24–29 Ma) are within the fossil age range of the unit (minimum age of Pliocene). These young cooled grains of the Miocene peak have the same U/Pb age distribution as those that represent the Eocene peak in both formations (i.e., crystallization at ~59, ~71, ~94, and ~147–159 Ma). U/Pb and FT age comparisons show that the source terrain has a long-lived Early Cretaceous to Paleocene geochronological signal. Therefore, the Miocene population does not represent a volcanic source. As such, possible sources of the Miocene DZFT population have one of two characteristics: (1) a variable, rapidly exhuming young source terrain or (2) subvolcanic or hypabyssal intrusions that reset near-surface rocks with a wide range of crystallization ages.

Analysis of the Eocene and Oligocene age populations reveals important details of the source terrain. The Oligocene peaks of the DZFT and U/Pb age results (>50% of the zircon grains represented) of the Kulthieth and Poul Creek formations are almost identical. U/Pb ages of the same grains analyzed by the DZFT method yield concordant age populations of ~59, ~71, ~94, and ~147–159 Ma. The U/Pb ages are all older (most much older) than all single-grain DZFT determinations, suggesting that these populations are not volcanic but instead

Figure 6. *A*, Histogram comparing the ~30-Ma detrital zircon fission-track (DZFT)-determined grain age population versus their equivalent U/Pb-determined age from the Kulthieth Formation. No single grain shares an identical age for both systems. *B*, DZFT grain dated by both DZFT analysis and subsequent laser-ablation ICPMS U/Pb analysis. The DZFT-determined cooling age is 23.9 ± 3.0 Ma (1σ), and the equivalent U/Pb-determined crystallization age is 51.9 ± 1.4 Ma (1σ). *C*, Histogram comparing the ~30-Ma DZFT-dated grain age population versus equivalent U/Pb-determined age. *D*, Scatterplot of U/Pb-determined (Ma) versus DZFT-determined (Ma) ages for single grains from the Poul Creek Formation. If a single grain had an identical age for both systems, it would plot on the 1 : 1 volcanic grain regression line. *E*, Histogram comparing the ~20-Ma DZFT-dated grain age population versus associated U/Pb-determined age. Single grains do not have identical ages for both systems. *F*, Scatterplot of U/Pb-determined (Ma) versus DZFT-determined (Ma) ages for single grains from the Yakataga Formation.

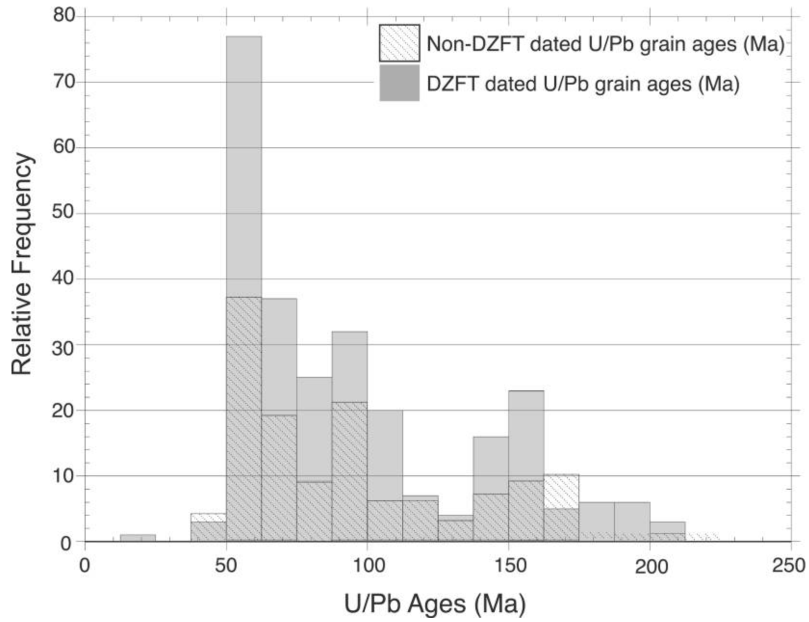


Figure 7. Single-grain laser-ablation U/Pb-determined crystallization age distributions and their associated single-grain detrital zircon fission-track (DZFT) cooling ages versus randomly selected single-grain laser-ablation U/Pb-determined crystallization ages. The age distributions represented are nearly identical.

are derived from exhumed rock. The Eocene FT age populations represent U/Pb crystallization ages ranging from 50 to 100 Ma; therefore, it is likely that this source is a significant belt of Eocene-cooled Cretaceous plutons.

If deposition of the Kulthieth and Poul Creek formations is within the bounds of the fossil age constraints, lag time (cooling to deposition) can be established for peak ages. If we assume several key parameters, exhumation rates can be estimated for the source rock to the Kulthieth and Poul Creek formations. These assumptions include (1) a geothermal gradient of 25°C/km, (2) a DZFT closure temperature of 240°C, and (3) the Miocene peak age range as a proxy for depositional age. These parameters provide estimated exhumation rates (for the Eocene peak) of 0.35–1.25 km/m.yr. for the source rock to the Kulthieth Formation and 0.4–1.25 km/m.yr. for the source rock to the Poul Creek Formation, giving a mean exhumation rate of 0.75 km/m.yr. Therefore, the potential source terrain is likely to have exhumed moderately fast in the Eocene to Oligocene, provided that the initial assumptions are valid.

Yakataga Formation. Sedimentary petrography of the Yakataga Formation indicates intermixing of sediment derived from two or more sources, but a key difference is a significant influx of rock fragments compared with the Poul Creek and Kulthieth formations (Plafker 1987; Eyles and Lagoe 1990; Harbor and Warburton 1993). Most lithic fragments in the Yakataga are sedimentary, metasedimentary, and volcanic rock fragments, which are likely derived from the nearby CPW composite terrane.

All Yakataga Formation samples have multiple DZFT age populations: Late Miocene (P_{1a} at ~8 Ma, ~5%), Middle Miocene (P_1 at ~15–17 Ma, ~40%, and P_2 at ~21–30 Ma), Oligocene (P_3 at ~30–35 Ma, ~30%–50%), and a minor older Eocene population (P_4 at 68–77 Ma, 11%–30%). The Oligocene and Eocene age populations (P_2, P_3, and P_4) are statistically identical to DZFT cooling ages in the underlying Poul Creek and Kulthieth formations, but the young Middle Miocene population (P_1) is unique and distinctive to the Yakataga Formation.

At this point it is useful to consider the older Yakataga populations (P_2, P_3, and P_4) in relation to those in the Kulthieth and Poul Creek formations. U/Pb crystallization ages were compared with DZFT cooling ages for specific grain age populations to determine whether the source(s) of the older P_2, P_3, and P_4 were influenced strongly by either volcanic or plutonic activity. Crystallization ages range from Cretaceous to Early Tertiary, suggesting that the original source of sediment to the Yakataga Formation is identical to that of the Poul Creek and Kulthieth formations. The U/Pb crystallization ages are consistently older than the DZFT cooling ages, indicating that these ages do not represent first-cycle volcanic rocks. In fact, one surprising finding is that none of the double-dated grains was demonstrably volcanic, which implies a lack of a significant active volcanic source for all of these units.

The Middle Miocene DZFT population (∼15–17 Ma) occurs only in the Yakataga Formation. U/Pb ages on the same grains used for DZFT analysis indicate the original crystallization age range from the Cretaceous to the Early Tertiary, with a distinct population of grain ages at 50–55 Ma; therefore, this population represents exhumed source rocks. The large population of U/Pb crystallization ages of ∼50–55 Ma most likely represents an Eocene plutonic belt exhumed in the Miocene. An ideal candidate is the Sanak-Baranof plutonic belt that intruded the Chugach terrane at ∼50 Ma, with numerous plutons near the current location of the Yakutat terrane intruded (Bradley et al. 2003; Madsen et al. 2006).

It seems clear that the common peaks of the Poul Creek and Kulthieth formations carry over, in some way, to the Yakataga Formation, but the proportions are different (see fig. 4). These common peaks (ca. 25 and ca. 40 Ma) in the Yakataga Formation may reflect a dual source for that unit or recycling of the underlying Poul Creek and Kulthieth formations. Although neither option can be ruled out, we favor the latter because the Yakataga Formation locally sits unconformably on the Poul Creek and Kulthieth formations and these older units are clearly involved in the thrust belt. In addition, the sandstones appear to be relatively well mixed, which is less likely with dual sources feeding a single basin. It is also clear, however, that the Yakataga Formation records the emergence of a new thermotectonic terrane dominated by a cooling age of ca. 17 Ma; however, the overall age distribution in this new source has resulted in mixing of different component peaks.

To understand the grain age distribution of this new source region, we estimated simple mixing of two end member thermotectonic signatures by averaging all component ages of the Poul Creek and Yakataga formations and then assuming a ratio of all peaks to the dominant peak age (ca. 40 Ma). Using the ∼40-Ma peak age in the average Yakataga Formation, we removed the hypothetical Poul Creek and Kulthieth component and determined what was left over. This exercise suggests that the Yakataga Formation has captured a mixture of about 65% of the new terrane, while about 35% of its zircon signature can be ascribed to recycling of Poul Creek and Kulthieth rocks. We estimate that this new terrane has end member cooling ages of 8 Ma (5%), 17 Ma (47%), 26 Ma (31%), and 65–75 Ma or older (18%). The new source is likely the CPW terranes.

Of the 150 grains double dated from the Yakataga Formation, only a single grain with a similar Early Tertiary DZFT (9.8 Ma, $-6.1/+15.2$) and U/Pb age (∼19 ± 3.0 Ma; both within 2σ) may represent derivation from an active volcanic source. Because distinctive clasts in the Yakataga Formation can be linked to the adjacent CPW composite terrane, much or most of this unit likely derived from the collisional belt (Plafker 1987; Nokleberg et al. 2005). Therefore, ∼17- and 25-Ma cooling age populations suggest deposition associated with the erosion and exhumation of the Chugach terrane. If our analysis is correct, about 80% of the DZFT grain ages ascribed to the Chugach exhumation fall in these two intervals (17 and 25 Ma), so these ages are clearly very significant in the context of exhumation of the CPW terrane. This result suggests that the Chugach terrane experienced significant regional exhumation in the Tertiary (Armstrong 1988; Cook et al. 1991; Plafker et al. 1994; Butzer et al. 2004).

Regional Considerations

Implications for Transport. The southern option for Yakutat terrane transport suggests that its basement rocks originated off northern California to Washington and experienced continuous displacement (∼1500–2000 km) from ∼45 Ma to the Recent (Bruns 1983). The northern option suggests a more conservative short-traveled displacement (∼600 km) from the Late Eocene to the present, as recorded in its cover strata (cf. fig. 8; Plafker et al. 1994). The end point in both models is the collision with the CPW composite terrane from the Pliocene to the present. The crucial difference between these models is presumably recorded in the Eocene to Miocene cover rocks.

The northern option assumes some continuity of the terrane with the CPW terrane and allows reconstruction southward on strike-slip faults with known displacement (i.e., 600 km of Queen Charlotte–Fairweather Fault; see Plafker et al. 1994). In this reconstruction, the Yakutat might have originated at a latitude of Prince Rupert in north-central British Columbia or farther north, so the block spent much of its history adjacent to the northern part of the CPC (fig. 8). Only in the final stages of its evolution did it break loose, move northward, and collide with the Chugach terrane rocks.

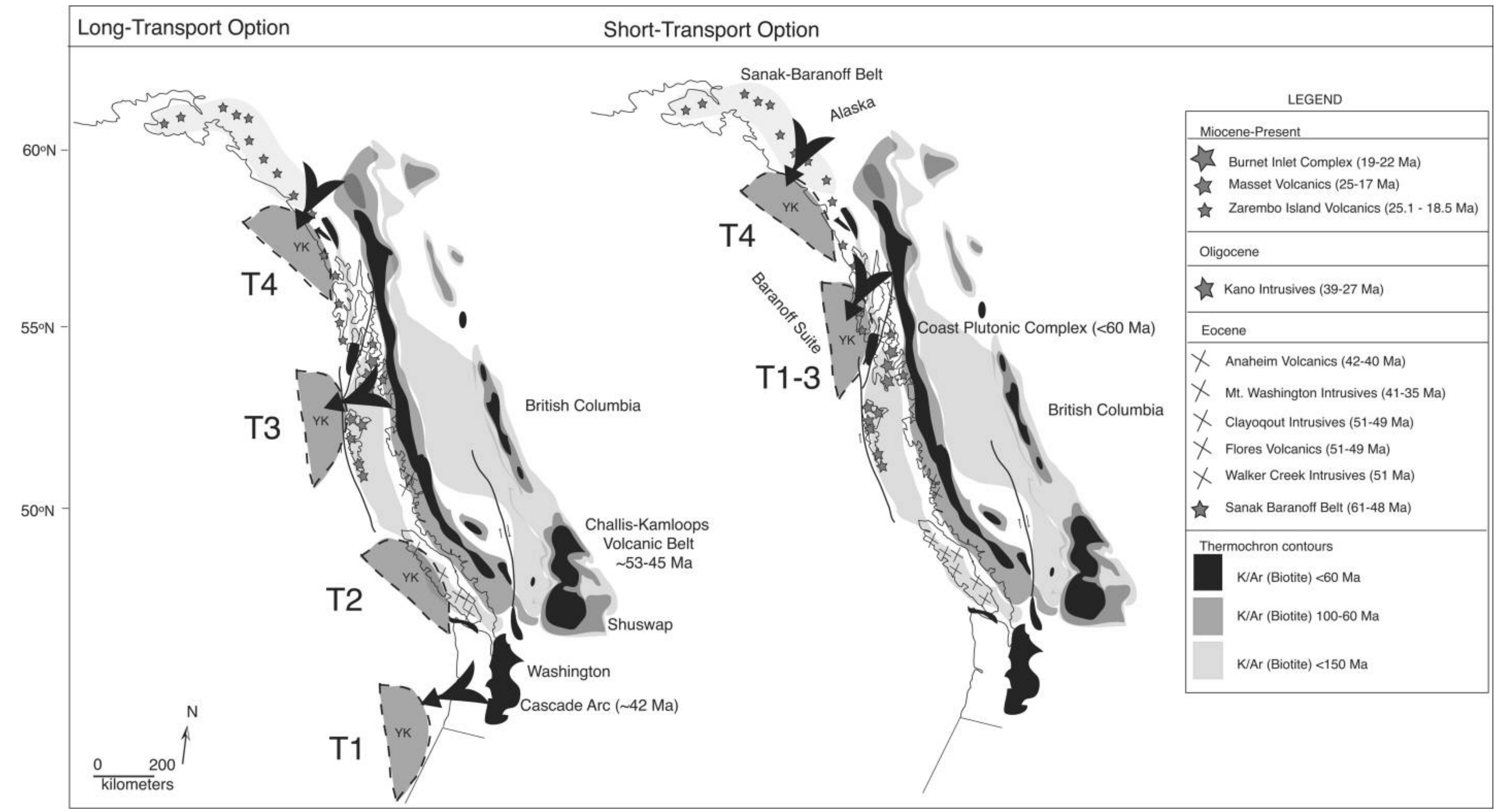


Figure 8. Long-transport versus short-transport Yakutat terrane (Eocene to the present) along the margin of the North American Cordillera. Terrane translation has been superimposed on the forearc magmatism thermotectonic overview of the coastline.

A major implication of this hypothesis is that the transport strata should have sampled what was more or less a single source terrane until final collision. There are two crucial implications of this short-transport hypothesis. One is that the CPC might have supplied much (or all) of the detritus to these units, and the other is that the only new or additional source rock would be the CPW terrane as it was uplifted and eroded during collision. In the northern option, the rapid-exhumed source is not obvious from the literature, but it may be represented by local rapid-exhumed rock along the Queen Charlotte–Fairweather Fault system. Uplift rates and possible driving mechanisms behind two major episodes of uplift in the northern CPC (~40 Ma and younger and ~10 Ma and younger) were based on zircon and apatite FT analysis (Parrish 1983). Intense plutonism within the northern CPC occurred during the Paleocene-Eocene, after which rapid cooling and related uplift within the range dominated. Subsidence within the Queen Charlotte Basin driven by localized cooling and subsequent extension coincides with periods of cooling and uplift within the Prince Rupert area (Harrison et al. 1979; Parrish 1983). With the southern option, plenty of source rocks exist for the later near-surface volcanic resetting (Cascade Arc), because deposition of the Poul Creek Formation coincides with isolated plutonism and volcanism near the present coastline from Washington to Alaska (Madsen et al. 2006; fig. 7).

As postulated, the southern option or long-transport hypothesis assumes that the Yakutat terrane originated at or near the Farallon-Pacific boundary (near present-day California-Washington) and moved on the Pacific plate since the Eocene (Bruns 1983). A major implication of this hypothesis is that the transport stratigraphy should have continuously sampled source rock along the continental framework. There are several implications of this long-transport hypothesis. One is that during the early part of the terrane's journey, the cover rocks to the terrane would have been derived from volcanic rocks of the Cascade Arc (active since ~45 Ma). Another is that a heterogeneous provenance should be expected as the block traveled along the Cordilleran margin. Because the lack of volcanic grains within the young Miocene peak rules out a volcanic-dominated source for the Kulthieth and Poul Creek formations, the data do not support either of these possibilities.

On the other hand, there is considerable support for the northern option. The northern CPC (north of Prince Rupert) has moderate to high rates of exhumation and a distinct lack of volcanic rock (Parrish 1983; Madsen et al. 2006). Overall geologic history of the region is dominated by metamorphic episodes recorded within the western metamorphic belt and associated plutonism north of Prince Rupert within the Admiralty Island and Revillagigedo Island areas (Cook et al. 1991; Cook and Crawford 1994). Onset of rapid uplift of portions of the western metamorphic belt coincides with transtension from changing plate motions at ~55 Ma associated with the Kula plate (Lonsdale 1988; Stock and Molnar 1988; Cook et al. 1991; Cook and Crawford 1994; Madsen et al. 2006). Increased exhumation is linked to differential tilting of crustal blocks along the western axis of the Coast Range boundary (Cook et al. 1991). Extension occurred across the region in the late Tertiary, accommodated by N- and NW-trending normal faults (Rohr and Dietrich 1992; Evenchick et al. 1999). Two episodes of forearc plutonism associated with changes in plate motion and subsequent extension along the northern CPC and southeastern Alaskan panhandle were dominated by the emplacement of the Sanak-Baranof belt, which progressed from east to west across the southeastern Alaskan panhandle to the Aleutians from ~65 to 50 Ma (Bradley et al. 2003), and the emplacement of the Burnett Inlet intrusive complex and Zarembo Island volcanics from ~26 to 17 Ma (Crawford and Crawford 1991; Lindline et al. 2004). This timing agrees with K-Ar biotite ages of 25.6–17.3 Ma (Brew et al. 1984) from shallow-level plutonic rocks on Kupreanof, Zarembo, and Etolin islands (ca. 20 Ma) and rhyolite dikes (15 Ma) in the Coast Mountains east of the study area.

Implications of Source Area Constraints. The wide differences in crystalline ages and cooling ages indicate that virtually all units in the Yakutat terrane did not sample a significant volcanic source. Also, homogeneity characterizes the Kulthieth and Poul Creek formations, which have a nearly identical provenance. If the Yakutat terrane originated off the coast of northern California or Washington, then the stratigraphy should have captured sediment shed off of the Cascade Arc and the southern CPC on the early part of its journey (Eocene-Oligocene; i.e., Kulthieth Formation). However, several attributes of the sedimentary signal favor a northern option and seem to rule out a far-traveled southern path of the cover strata: (1) the zircon age distribution is remarkably uniform in the entire stratigraphy of the Yakutat terrane, which would seem to favor a simple history adjacent to one geochronologically and thermochronologically distinct source region, and (2) the units are distinct, lacking in volcanic zircons (where crystallization ≈ cooling age). At this point we suggest that the far-traveled southern option can be ruled out and instead examine the implications of the northern option.

One of the most distinctive aspects of the U/Pb ages in the Kulthieth, Poul Creek, and Yakataga formations is the similarity to the known magmatic signal recorded in the northern CPC (as summarized in Armstrong 1988; Cook et al. 1991; Cook and Crawford 1994). By combining all of the U/Pb-determined crystallization ages for the Kulthieth and Poul Creek formations (which are nearly identical) and comparing them with the compilation discussed by Armstrong (1988), a direct comparison of Yakutat and CPC U/Pb magmatic events can be made. The Kulthieth and Poul Creek formations record a long-lived continuous crystallization record with a distinct lull of magmatic activity at ca. 150 Ma, corresponding to a well-documented regional lull in magmatic activity in the northern CPC (Armstrong 1988; Armstrong and Ward 1991). There is a continuous long-lived plutonic signal provided by the CPC source terrain from ~50 to 220 Ma (Armstrong 1988). The DZFT cooling age populations that correspond to Eocene to Cretaceous populations of U/Pb-dated grains and episodes of magmatism within the CPC are represented by the Paleocene-Eocene populations within the Kulthieth and Poul Creek formations (~97–47 Ma). Again, this comparison would favor a more northerly option for the source of the pre-Pliocene Yakutat stratigraphy because the northern CPC has higher exhumation rates (Parrish 1983; Armstrong 1988; Cook et al. 1991).

The zircon ages in the Yakataga Formation demonstrate that the DZFT age of the Miocene (young peak) population first appears in this unit. In addition, the U/Pb ages for younger DZFT cooled grains (ca. 26 Ma) were crystallized (U/Pb) at ~51 Ma. Together these results indicate that the Yakataga Formation tapped a completely new source terrain for the younger population, but its older components are identical to those in the Kulthieth and Poul Creek formations. We assume, like many others, that the Yakataga Formation was deposited relatively near its present location (Eyles and Lagoe 1990). Two major plutonic episodes are recorded in the nearby CPW composite terranes (Bradley et al. 2003) that were intruded by the Paleocene to Early Eocene (60–50 Ma) and Late Eocene Sanak-Baranof plutonic belt. The first plutonic phase ranges from ~61 to 50 Ma, and ages decrease from west to east. The young ages of ~50 Ma are on Baranof Island in southeastern Alaska (Cowan 1982, 2003).

Conclusions

Double dating of detrital zircons by the FT and U/Pb techniques is a powerful tool in evaluating provenance. The sediment provenance and zircon geo- and thermochronology from the Yakutat terrane shows that most sediment was derived from a Tertiary-cooled, Cretaceous to Early Tertiary plutonic complex, most likely the northern CPC and adjacent terranes. Paleocene to Eocene strata record a long-lived, nonvolcanic source terrain that crystallized from ~50 to 220 Ma and cooled from ~48 to 110 Ma.

The overall pattern of grain ages favors the northern transport option, based on the (1) uniform provenance of the Kulthieth and Poul Creek formations; (2) the overall grain age distribution, which has common elements throughout; and (3) the distinct lack of volcanic zircons. The southern option can be ruled out for the cover strata mainly due to the lack of volcanic grains that would be expected in the stratigraphy during continuous transport of the terrane along route.

However, because we have data only on Upper Eocene and younger rocks, a far-traveled option for the Middle Eocene and older basement rocks cannot be excluded (see Bruns 1983; Cowan 2003). In the eastern part of our study area, the Yakutat cover strata rest unconformably on the Orca Group, part of the CPW terrane (Plafker et al. 1994). A number of lines of evidence suggest that the CPW was far-traveled and displaced along the margin of the Cordillera after intrusion of the Sanak-Baranof plutonic suite but before deposition of cover strata. The most compelling evidence is the geologic similarities between the ~50-Ma metamorphic rocks on Baranof Island (SE Alaska) and the Leech River Schist (southern Vancouver Island), which suggest that the southern part of the CPW was as far south as the Washington/British Columbia border at ca. 50 Ma and that these two distinctive metamorphic units were contiguous. After metamorphism of these units, the CPW was detached and rapidly translated northward by about 1100 km to the northern margin of the Cordillera (Cowan 2003). After this displacement, rocks similar to those in the southern part of the CPW remain in the border area between Washington and British Columbia (i.e., Cowan 2003). Our analysis would suggest that this 1100-km transport was likely complete by deposition of the unconformably overlying Kulthieth Formation at about 40 Ma.

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