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SOUTHWESTERN LAURENTIAN ZIRCONS IN UPPER CRETACEOUS FLYSCH OF THE CHUGACH-PRINCE WILLIAM TERRANE IN ALASKA

JOHN I. GARVER*,† and CAMERON M. DAVIDSON**

ABSTRACT. The Chugach-Prince William (CPW) terrane in southern Alaska is dominated by thick imbricated flysch, mainly Maastrichtian to Paleocene, that represents one of the thickest accretionary complexes in the world. Detrital zircons from sandstones from across the belt are dominated by grains with crystallization ages close to the age of deposition, and hence the source region supported a long-lived Late Cretaceous to Paleocene volcanic arc. The metaplutonic basement that supported this arc was made of rocks with Mesozoic zircons (Jurassic), with a minor fraction of Paleozoic (Devonian) and Precambrian grains. There is continuity of grain ages across the belt from the Shumagin Islands in the west to the eastern localities, including the Yakutat Group. Positive εHf isotopic ratios in zircons (from the arc and basement) are consistent with melting of a relatively juvenile source, and the leading source candidate is the Coast Plutonic Complex that intrudes the Wrangellia composite terrane.

The small fraction of Precambrian detrital zircons, typically <5 percent, reveal two cohorts with distinct histories. A western cohort of Precambrian grains from Shumagins, Kodiak, and Prince William Sound have grain age populations and isotopic signatures consistent with a northern Laurentian source. These grains have a wide range of ages, but are dominated by populations between 1810 to 1870 Ma and 2520 to 2680 Ma. Collectively these grains have εHf (t) from +13.9 to –21.1, but most grains >1800 Ma have negative εHf (t) values consistent with an evolved source. Raman spectroscopy on zircons from this suite indicates total radiation damage and internal disorder is considerable and comparable to 0.5 to 1.0 Gyr of accumulated damage. Thus the source rocks had to have resided high in the crustal column for most of the Phanerozoic. An eastern cohort of Precambrian grains have grain-ages and an isotopic signature consistent with a southern Laurentian source – mainly Yavapai-Mazatzal, Mojave and the Granite-Rhyolite province of the southwest United States. These zircons are dominated by populations at ~1380 Ma, ~1485 Ma, and ~1722 Ma and εHf (t) values are mostly positive, ranging from +11.7 to –3.4. All zircons between 1436 and 1716 Ma have positive εHf (t) values, which indicate juvenile source rocks, a unique and distinctive aspect of SW Laurentia. Total radiation damage and internal disorder in this suite of detrital grains is minimal and comparable to ~100 Myr of accumulated damage, which requires source rocks to have been heated to amphibolite grade in the Cretaceous. Thus the low radiation damage may require derivation from in and around the arc, and not farther inland.

We hypothesize that the majority of the flysch of the CPW terrane accumulated in an accretionary complex flanking what is now the Coast Plutonic Complex, but that zircons from the eastern cohort of the CPW were derived from rocks of the Sierran-Southern California-Peninsular Arc, which collapsed along a narrow tectonic corridor due to the subduction of the conjugate to the Shatsky Plateau in the Maastrichtian – the Mojave breach. This point source of southwestern Laurentian rocks allowed sediment with a distinct Precambrian signature to spill out into the forearc and thus part of the Chugach flysch shares a common history with part of the Franciscan Complex. We hypothesize that some of the Chugach flysch was deposited in a trench adjacent to this southwestern Laurentian point source and was subsequently displaced ~3200 km northward to Alaska.

Key words: Zircon, Provenance, Alaska, terrane translation, California, Hf isotopes, Raman spectroscopy.

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INTRODUCTION

An outstanding question in the assembly of the North American Cordillera is timing of accretion and the significance of coast-parallel translation of outboard terranes (Cowan and others, 1997). Controversy surrounds the amount of translation of the Cretaceous to Eocene flysch of the Chugach-Prince William terrane, a subduction complex that extends for ~2200 km along the southern Alaskan margin (fig. 1). Flysch of the Chugach-Prince William (CPW) terrane is inferred to represent one of the thickest accretionary complexes in the world (Plafker and others, 1994; Cowan, 2003). The CPW terrane is bounded to the north by the Border Ranges fault, which shows evidence of Tertiary dextral strike-slip faulting, and inboard terranes of the Wrangellia composite terrane (Peninsular, Wrangellia, Alexander) (Roeske and others, 2003). Most of the Chugach and Prince William terrane is composed of imbricated trench-fill turbidites (flysch) deposited over a relatively short interval of time (Campanian to Paleocene – *ca.* 75–55 Ma) and the volume of sediment is estimated to be ~3 million km^3 (Plafker and others, 1994).

Few studies have used *geologic tests* to evaluate apparent offset and possible ties to the south. A postulated link between the Baranof Schist in SE Alaska and the nearly identical Leech River Schist on Vancouver Island suggest they were contiguous at 50 Ma (fig. 1; Cowan, 2003). It has long been postulated that the sediment composition, volume, and provenance indicates that the Coast Plutonic Complex, largely in British Columbia, was the source to the flysch and thus at least some margin-parallel transport is required (Zuffa and others, 1980; Dumoulin, 1987; Sample and Reid, 2003; Amato and Pavlis, 2010). Leaf margin morphology of fossils in the mid-Cretaceous Winthrop Formation suggest an offset of 2200 km of rocks in the Methow basin (Miller and others, 2006). The source of detrital zircons in the Upper Cretaceous Nanaimo basin in southern Vancouver Island are controversial (compare Mahoney and others, 1999, and Housen and Beck, 1999). In any scenario, a considerable amount of the margin-parallel translation must be accommodated by the terrane-bounding Border Ranges fault system that allows for slip between the flysch of the Chugach and more inboard terranes (Cowan, 2003; Roeske and others, 2003; Pavlis and Roeske, 2007). Here we present U/Pb, Hf, and Raman data from detrital zircons that show this accretionary complex was derived from an active Cretaceous arc built on a Jurassic metaplutonic basement, and that some of these zircons were derived from southwestern Laurentia far to the south of their present position.

GEOLOGIC BACKGROUND

The Chugach terrane can be divided into an inboard assemblage of several small sub-terranes and an outboard flysch facies[1], which makes up about 90 percent of the terrane (Plafker and others, 1994; Amato and Pavlis, 2010). Along the belt, the turbiditic sandstone and interbedded shale (flysch) is represented by the Shumagin Formation, Kodiak Formation, Valdez Group, Yakutat Group, and the Sitka Graywacke (west to east). Although detached, the Yakutat Group is allied with the belt, and most likely the southernmost fragment prior to ~600 km of late Tertiary strike-slip movement (Plafker and others, 1994; Perry and others, 2009). These outboard flysch units of the Chugach are compositionally similar to Paleocene and Eocene flysch of the younger Prince William terrane, which is essentially the Paleocene to Eocene Orca Group in Prince William Sound, and the Paleocene Ghost Rocks on Kodiak (Dumoulin, 1987; Plafker and others, 1994). In this contribution, we are only concerned with flysch units of both the Chugach and the Prince William terrane that are Maastrichtian

[1] The word *Flysch* is widely used in the area for rhythmically interbedded lithic-rich sandstone and shale. All we have studied are marine turbidite sequences.

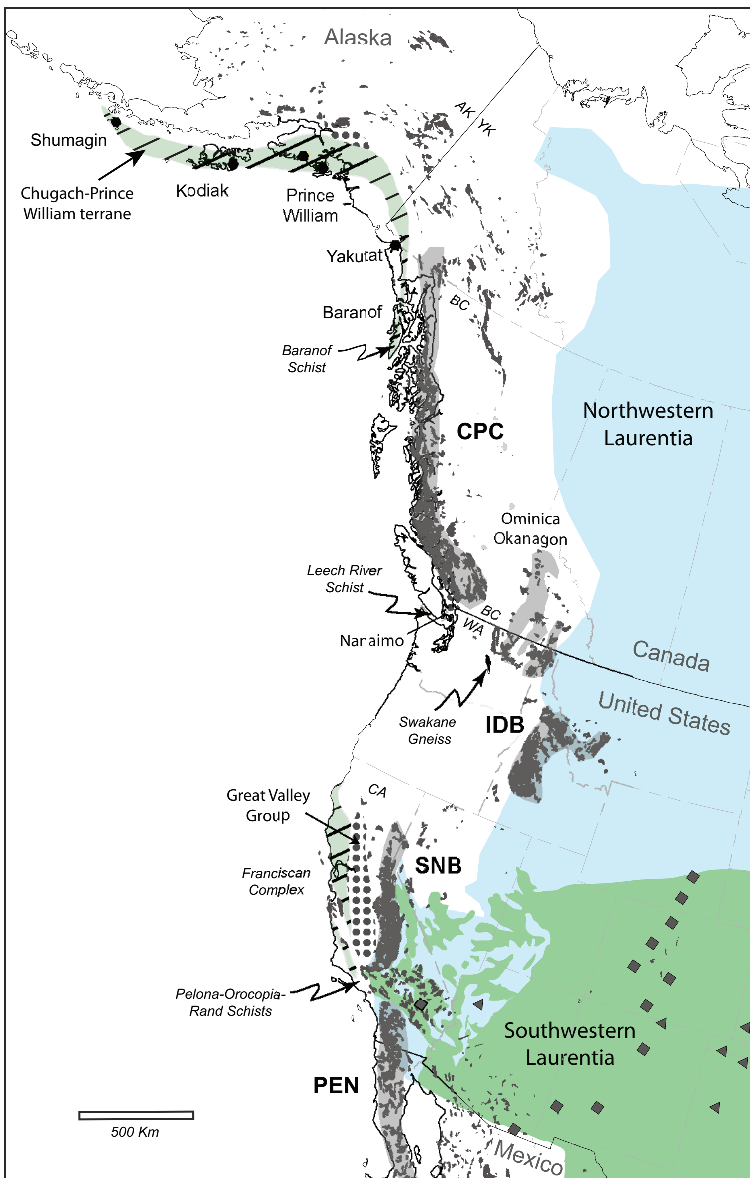

Fig. 1. Simplified map of western North America showing key tectonic elements related to the Chugach-Prince William terrane and California geology (modified from Piercey and Colpron, 2009; Lamaskin, 2012). Cretaceous and early Tertiary plutons shown in black and major belts shaded in gray (from Garrity and Soller, 2009). Principal isotopic ages of the North American Craton are simplified to show older Archean and Paleoproterozoic NW Laurentian units (blue), and younger Paleoproterozoic and Mesoproterozoic SW Laurentia units (green, primarily Yavapai-Mazatzal; anorogenic granites shown as squares and triangles). Primary Cretaceous batholithic complexes denoted as: CPC – Coast Plutonic Complex, IDB – Idaho Batholith, SNB – Sierran Nevada Batholith; PEN – Peninsular Ranges. Filled circles show the locations of the four sampling sites discussed in this study.

to Eocene in age (Cowan, 2003; Amato and Pavlis, 2010). The CPW accretionary complex was intruded by diachronous near-trench plutons of the Sanak-Baranof belt (SBB) inferred to be related to ridge-trench interaction of the Kula-Farallon or the Kula-Resurrection ridge (Bradley and others, 2003; Haeussler and others, 2003).

Paleomagnetic data indicate significant northward coast-parallel transport of rocks of the CPW and SBB plutons (Plumley and others, 1982; Coe and others, 1985; Bol and others, 1992; Gallen, ms, 2008; Housen and others, 2008; O'Connell, ms, 2008), although this conclusion has been, and remains, controversial (compare Haeussler and others, 2003; and Cowan, 2003). Paleomagnetic data from Paleocene rocks of the Resurrection ophiolite (57 Ma) indicate an original paleolatitude 13 ± 9° south of its present location (1430 ± 990 km – Bol and others, 1992). The slightly older Ghost Rocks on Kodiak Island show a mean value of 25 ± 7° of latitudinal displacement (~2750 ± 770 km) since about 60 to 62 Ma (Plumley and others, 1982). Recent detailed re-analysis of the Ghost Rocks produces a similar result suggesting they have been translated northward ~2500 ± 700 km (Gallen, ms, 2008; O'Connell, ms, 2008). Nonetheless, the nature of structural corrections, primary remnant magentization, possible remagentization, and movement on oceanic plates have led to controversy as to the significance of these data (Plafker and others, 1994; Haeussler and others, 2003; Cowan, 2003; Gallen, ms, 2008; Housen and others, 2008; O'Connell, ms, 2008).

A considerable amount of the required margin-parallel translation can be accommodated by the Border Ranges fault system (Roeske and others, 2003, 2007). This fault system is an important tectonic boundary in southern Alaska that separates the Chugach terrane from the elements of the Wrangellia superterrane and it almost certainly played a role in significant margin-parallel translation (Cowan, 2003; Roeske and others, 2003; Pavlis and Roeske, 2007). The fault system can be traced for 2000 km in southern Alaska, and almost everywhere exposed it has a clear record of Late Cretaceous to Tertiary dextral strike-slip faulting (Plafker and others, 1994; Pavlis and Roeske, 2007). The Hangitata fault segment in the eastern Chugach Mountains is a well-studied segment with a clear record of dextral slip, and geological relationships indicate that in this area, slip of 600 to 1000 km or more may have occurred between 70 and 52 Ma (Pavlis and Roeske, 2007). Elsewhere in the Chugach Mountains, the occurrence of ~50 Ma plutons, dikes, and sills in the fault, locally on either side, or cross-cutting the fault may indicate a lower limit for the timing of fault movement (Pavlis and Roeske, 2007). Reconstruction of faults within the terrane show that there was ~150 to 200 km of dextral motion within the Chugach terrane during the narrow time interval of 52 to 54 Ma (Sharman and others, 2012). While several areas have similar-aged intrusive rocks on either side of the fault, the mapped segment on Chichagof and Yakobi islands (in SE Alaska) is inferred to have plutons that cross cut the mapped fault trace (at *ca.* 50 Ma). In our analysis, we conclude that there is weight to the argument that this segment of the fault may be pinned by 50 Ma plutonic rocks (see Haeussler and others, 2003), but we entertain the possibility that these ambiguous relationships actually permit younger slip on the BRF system (see Cowan, 2003). A subtle point in this discussion is the relationship of the flysch to older elements of the Chugach terrane. There is virtually no evidence to suggest that the flysch of the CPW was fixed to the inboard units in the Cretaceous and early Tertiary, therefore the relation of the older Chugach rocks (mélange and blueschist) and the main part of the Chugach (Upper Cretaceous flysch) remains an open question.

There is continuity of flysch units across the major part of the CPW belt, with the exception of the small fragment that makes part of the basement to the Yakutat microplate (Plafker and others, 1994). These rocks include the Yakatut Group, which includes Campanian and Maastrichtian mélange and arkose offset by modern motion on the Queen Charlotte-Fairweather fault system. A key concern in our work is the small slice of Chugach rocks that make up the Upper Cretaceous (Maastrichtian) Yakutat Group exposed in and around Yakutat Bay (fig. 1). Yakutat Group rocks restore to a position where they are the southeastern extent of the Chugach terrane (Plafker and others, 1994; Perry and others, 2010). Seismic refraction data show that the Yakutat Group rocks in this area are a thin wedge above underthrust Yakutat mafic crust, inferred to be oceanic plateau with affinities and an alliance with the Siletz terrane in the Pacific Northwest (Bruns, 1983; Worthington and others, 2012).

METHODS

We used standard techniques to separate and analyze detrital zircons from the flysch of the CPW terrane from four study sites across the southern tier of Alaska. Zircon separates were split, and half were fission-track dated (not reported here), and half were dated by the U/Pb technique (Appendix A; http://earth.geology.yale.edu/~ajs/SupplementaryData/2015/Garver). Many of the dated zircons were then analyzed with Raman spectroscopy to assess internal crystallinity. Hf isotope ratios were collected on Precambrian zircons and select zircons from distinctive Phanerozoic populations to determine the isotopic signature of the source region (Appendix B; http://earth.geology.yale.edu/~ajs/SupplementaryData/2015/Garver). Thus most of the Precambrian grains in our study have been analyzed by all three techniques providing us with the time and nature of crustal contamination during crystallization and total accumulated radiation damage since cooling.

U/Pb and Hf isotope measurements were conducted at the University of Arizona Laserchron Center using standard methods reported in Appendices A and B (http://earth.geology.yale.edu/~ajs/SupplementaryData/2015/Garver). We used a combined method of random dating (typically 100 grains) and dating zircons that were hand-selected based on shape and color to enhance the number of Precambrian grains in each sample. Therefore, most samples have n>100. For this contribution, we focused on samples with Maastrichian to Paleocene maximum depositional ages as determined using Age Pick, an Excel macro provided by G. Gehrels. For the εHf (t) vs. U/Pb age plot we show 363 detrital zircons from the Chugach Prince William terrane. Depleted mantle curve is from Vervoort and Blichert-Toft (1999), Hf crustal evolution curves (thin dashed lines) are plotted using $^{176}Lu/^{177}Hf = 0.0115$ (Vervoort and Patchett, 1996; Vervoort and others, 1999) and chondritic uniform reservoir (CHUR) is from Bouvier and others (2008).

Raman measurements were made with a Bruker Optics Senterra® Spectrometer using 633 nm He-Ne laser and signal was captured by a thermoelectric-cooled CCD detector. Measurements were made with a laser power of 20 mW, and an aperture of 25×1000 μm and an integration time of 5 to 20 seconds. Gaussian-Lorenzian peak fitting was used to characterize the ν_1SiO_4 (~974 cm-1) symmetric stretching and the ν_3SiO_4 (~1007 cm-1) antisymmetric stretching bond. Our reference zircons include 18 grains from Sri Lanka (best fit, uranium determined by neutron irradiation), 20 grains from the 2 Ma Huckleberry Ridge Tuff, 19 grains that range from 302 to 370 Ma (midpoint line of primary field), and 51 grains that range from 70 to 80 Ma (midpoint line of primary field,); for the latter three, uranium was determined by LA-ICPMS during U/Pb analysis. Error is estimated at 0.2 wavenumbers based in duplicate measurements, and uranium determination is estimated at 10 percent. Our U/Pb data are reported in Olivas, 2012; Olivas and others, 2012; Davidson and others, 2013; Hilbert-Wolf, 2012a, 2012b; Pettiette, 2013; Pettiette and others, 2013; Roe and others, 2013; Roe, 2013. The Hf data are originally reported in Davidson and others (2013), Roberts and others (2013) and Roberts (2013a, 2013b) (See Appendix A; http://earth.geology.yale.edu/~ajs/SupplementaryData/2015/Garver).

RESULTS

U/Pb Dating

We dated 4383 detrital grains and in this paper we focus on 1765 dates from the age-correlative Upper Cretaceous to Paleocene flysch units of the Shumagin Formation,

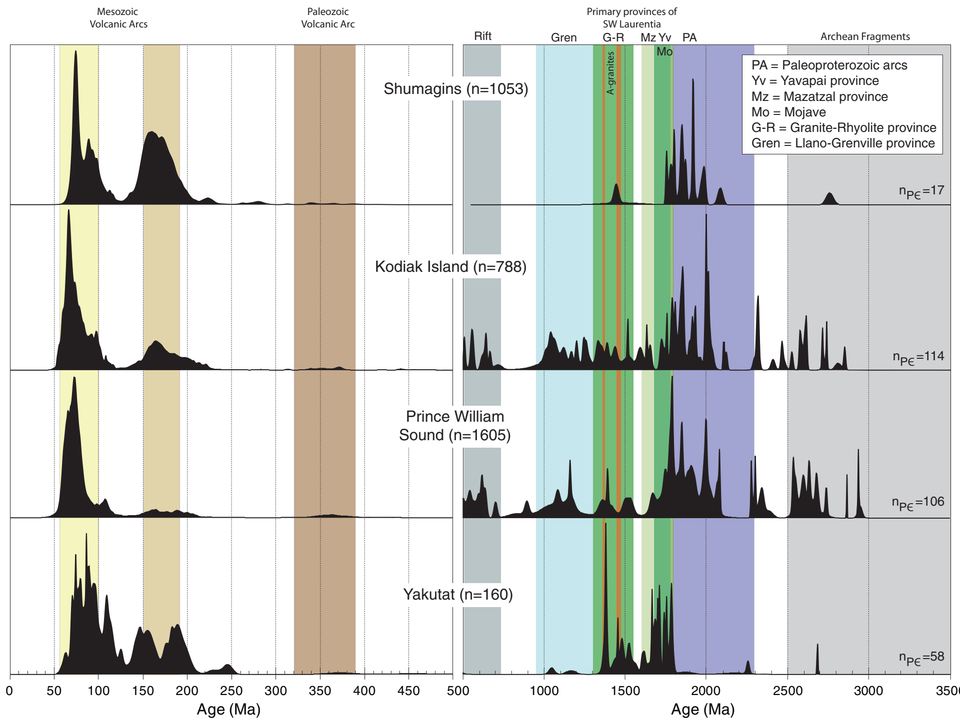

Fig. 2. Compilation of U/Pb ages of detrital zircon from the Upper Cretaceous to Paleocene flysch of the Chugach-Prince William terrane. Note that the age and relative frequency of zircon grain ages are shown on two separate plots with different scaling on the ordinate and abscissa. Shaded ages are those primary crustal ages recognized in North America (see Goodge and Vervoort, 2006; Whitmeyer and Karlstrom, 2007).

Kodiak Formation and Ghost Rocks, Valdez and Orca Groups, and Yakutat Group (from west to east, fig. 1). All samples are dominated by Jurassic and Cretaceous grains, undoubtedly derived from a segment of the magmatic arc rocks that occur widely in the western Cordillera (fig. 2). The leading source candidate is the Coast Plutonic Complex that intrudes the Wrangellia composite terrane and the adjacent thrust belt (Farmer and others, 1993; Sample and Reid, 2003; Gehrels and others, 2009). In all samples there is a small but significant fraction of Precambrian grains that vary in abundance (~1 – 10%) and age distribution. These Precambrian zircons provide information about the nature of basement terranes and they fall into two distinct cohorts: (1) zircons of the Shumagin, Kodiak, Valdez, and Orca have a wide range of ages with modes at 1810 to 1870 Ma and 2520 to 2680 Ma, similar to a northern Laurentian source; (2) zircons of the Yakutat Group have modes at *ca.* 1380 Ma, 1485 Ma, and 1722 Ma, which are identical to the Yavapai-Mazatzal and Mojave provinces (1.6–1.8 Ga) and the Granite-Rhyolite province (1.3–1.4 Ga) of southern Laurentia. The Yakutat zircons have two populations that correspond to the specific modes of anorogenic granites in the SW US, which have modes at 1370 and 1450 to 1475 Ma (Goodge and Vervoort, 2006; Dickinson and others, 2012). Perhaps most importantly, this cohort lacks the wide range of grain ages typical of a northern Laurentian source (Laskowski and others, 2013).

Hf Isotopes

Our data set includes age-corrected Hf isotope ratios ($^{176}Hf/^{177}Hf$) for 363 detrital zircons previously dated by U/Pb, and this data set includes 213 Precambrian grains from the Kodiak and Ghost Rocks Formations, the Orca Group, and the Yakutat Group (fig. 3). These isotopic measurements are used to understand crustal evolution and are typically expressed in epsilon notation [εHf (t)] where the measured ^{176}Hf/^{177}Hf is normalized to the ^{176}Hf/^{177}Hf of undifferentiated mantle (chondritic uniform reservoir or CHUR – see fig. 3). In general, positive εHf (t) values represent a larger component of juvenile crust in the source region during partial melting of continental crust to form zircon-bearing granites, and negative εHf (t) values suggest a larger component of isotopically evolved, or older crustal material in the source region.

The western cohort of Precambrian zircons (Shumagin Formation, Kodiak and Ghost Rocks Formations, and the Orca Group) with U/Pb age populations at 1810 to 1870 Ma and 2520 to 2680 Ma have εHf (t) from +13.9 to –21.1. The eastern cohort (Yakutat Group) contrasts sharply with U/Pb age populations at 1380 to 1450 Ma and 1710 to 1740 Ma, because the εHf (t) values are mostly positive, ranging from +11.7 to –3.4. In fact, all detrital zircons between 1436 and 1716 Ma have positive εHf (t) values, which indicate juvenile source rocks. εHf (t) values of zircons from the Jurassic and Cretaceous arcs are strongly positive indicating derivation from a relatively juvenile source region, and in this case young outboard accreted terranes (fig. 3); notable exceptions are five Cretaceous grains from Yakutat (-12.3 to -26.5), which suggest derivation from the partial melting of Mesoproterozoic crust, likely Yavapai-Mazatzal in the SW US as discussed below.

There are very few options in North America for an isotopically juvenile crustal signature in zircons with this narrow range of specific Precambrian ages. The isotopic signature from Yavapai-Mazatzal rocks in the southwestern United States is distinct from all other basement units of this age because it is so juvenile and these rocks are intruded by the isotopically distinctive anorogenic granites (Goodge and Vervoort, 2006; Goodge and others, 2008). Assuming a typical value for the ^{176}Lu/^{177}Hf ratio of the crust (^{176}Lu/^{177}Hf =0.0115, Vervoort and others, 1999) and ignoring the complexities of mixing between different isotopic reservoirs, we calculate approximate mantle separation ages of 1.6 to 2.2 Ga for zircons that fall in this juvenile window, which is essentially identical with Yavapai-Mazatzal mantle separation ages (for example Goodge and Vervoort, 2006; Goodge and others, 2008). The initial εHf (t) values are highest in the Granite-Rhyolite province and the Central and Western Yavapai where they range from $+7.0 \pm 0.9$ to $+1.4 \pm 0.6$ (Goodge and Vervoort, 2006). The isotopic signature of the anorogenic granites that intrude Yavapai-Mazatzal rocks in southwestern Laurasia are also distinctive because it shows intrusion was through juvenile crust. The granite intrusions have modes at 1370 and 1450 to 1475 Ma and εHf(t) values similar to, but slightly lower than, host terranes and in the southwestern United States the average is between +0.2 and +3.3: the same range as our detrital grains (Goodge and Vervoort, 2006).

We would note that it is possible to get similar Mesoproterozoic grain ages from the Belt Supergroup in Idaho-Montana-Alberta. However, any detrital zircons from this area would be dominated by zircons between 1640 and 1860 Ma, and would likely have a component of Archean zircons between 2550 and 2750 Ma (Ross and Villeneuve, 2003; Link and others, 2007; Stewart and others, 2010). The Belt Supergroup is known to have a distinctive western source area, now gone, which contributed a very large and distinctive population of zircons at 1730 Ma (Link and others, 2013). But what is important about these populations is that the initial Hf isotope values for candidate zircons from the Belt Supergroup have a much wider range of εHf (t) with values between +5 and −9 (Stewart and others, 2010), which is much greater and wider than the +7–0 εHf (t) range for A-type magmatic zircons from southwestern Laurentia (Goodge and Vervoort, 2006), and those detrital grains in the Yakutat Group.

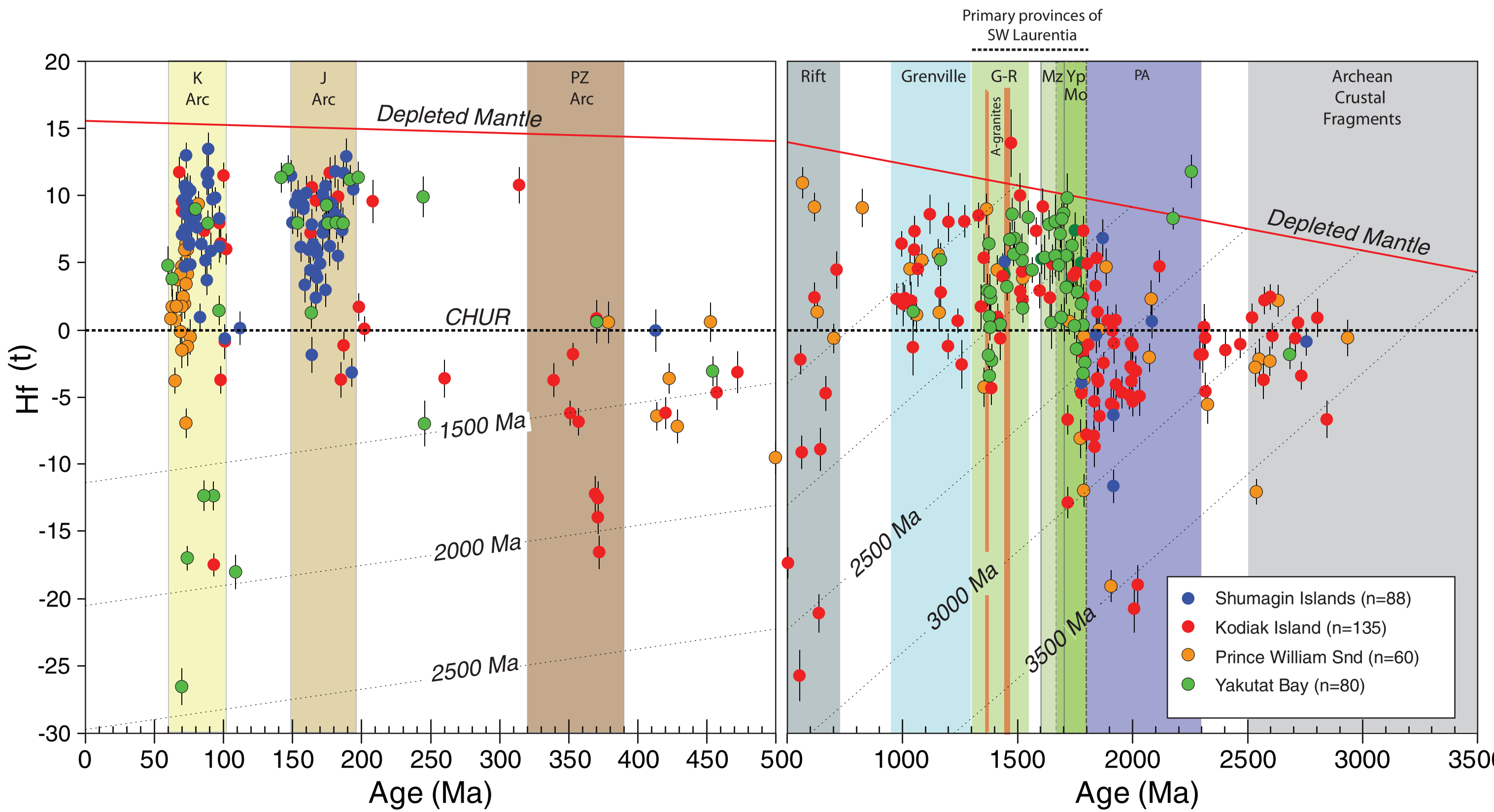

Fig. 3. Hafnium isotope data from detrital zircon of the CPW terrane. Depleted mantle curve from Vervoort and Blichert-Toft (1999), and Hf crustal evolution curves (thin dashed lines) are plotted using $^{176}Lu/^{177}Hf = 0.0115$ (Vervoort and Patchett, 1996; Vervoort and Blichert-Toft, 1999). Chondritic uniform reservoir (CHUR) is from Bouvier and others (2008). Bounds of shading of crustal ages defined in Whitmeyer and Karlstrom, 2006; and Goodge and Vervoort, 2006; Nelson and Colpron, 2007; Laskowski and others, 2013. See text for discussion.

The most isotopically evolved zircons from the Cretaceous arc (εHf (t) = −12.3 to −26.5) are compatible with late Mesozoic intrusion into Precambrian basement of Yavapai-Mazatzal age (fig. 3). This finding means that some of the arc volcanics may have intruded directly through and onto Precambrian basement with a Yavapai-Mazatzal isotopic signature. This is potentially an important observation because part of the southern California arc in the Mojave is built on Precambrian rocks, and this would be the only place in the entire North American Cordillera where this relationship is observed (Jacobson and others, 2011).

Raman Spectroscopy

We used μ-Raman to measure relative crystallinity of 190 U/Pb-dated Precambrian detrital zircon grains to understand their long-term thermal evolution and metamorphic history (fig. 4). Loss of crystallinity in typical zircon occurs with time through accumulation of alpha damage provided the host rocks reside at high crustal levels thus inhibiting annealing and recrystallization; high temperatures and metamorphic conditions reverses the process (Nasdala and others, 1995; Marsellos and Garver, 2010). The Precambrian zircon grains fall into two distinct arrays of radiation damage as indicated by the position of the $\nu_3(SiO_4)$ active mode: 1) the western cohort have considerable disorder and fall on a common array (fig. 4). We estimate that these grains have likely accumulated radiation damage for 0.5 to 1.0 Gyr (more damage than the 565 Ma Sri Lankan age standard); (2) the eastern cohort have very little disorder and have likely only accumulated radiation damage since the late Mesozoic (*ca.* 100 Ma, similar to Mesozoic volcanic grains in our data set). Thus the integrated radiation damage (and disorder) of this latter suite of zircons indicate derivation from a source of Precambrian rocks that have been heated or metamorphosed to the point where accumulated radiation damage had been fully annealed in the Cretaceous.

DISCUSSION

By the Late Cretaceous and Paleocene when the flysch of the Chugach-Prince William terrane rocks was deposited, the North American Cordillera was high standing, and outboard units were dominated by detritus from adjacent continental arc rocks. Thus the grain-age distribution in Upper Cretaceous basin sequences on the western margin of the Cordillera is dominated by grains that reflect the Cretaceous and Late Jurassic magmatic pulses (Gehrels and others, 2009; Lamaskin, 2012). The high-standing North American Cordillera isolated subduction and strike-slip settings along the western edge of the Cordillera from most of the Precambrian basement rocks of the interior, hence it is unusual to find Precambrian zircons in outboard units (Lamaskin, 2012; Sharman and others, 2013). The southern California margin and the Idaho sector are notable exceptions.

A distinct feature of the Southern California sector of the Cordillera is the disruption of the Cretaceous arc rocks. In the Late Cretaceous, Precambrian rocks of southwestern Laurentia were disrupted, uplifted, and readily available for sediment delivery to the forearc in the Maastrichtian due to subduction of the conjugate to the Shatsky Plateau (Liu and others, 2010; Sharman and others, 2013). In the wake of subduction of the Shatsky conjugate, upper-plate rocks of the Sierran-Southern California-Peninsular Arc collapsed along a narrow tectonic corridor centered on the Mojave area of southern California and provided a unique sediment pathway to the forearc of distinctive and age-diagnostic sediment from the southwestern Laurentian basement units (Jacobson and others, 2011; Sharman and others, 2013). In the immediate vicinity of the breach, these rocks include the Yavapai-Mazatzal, anorogenic granites, the Mojave province, and superimposed volcanic rocks. Of these basement units, the Yavapai-Mazatzal (1.6–1.8 Ga) and the Anorogenic granites (1.4–1.5 Ga) are distinctive because of their ages and isotopic signature.

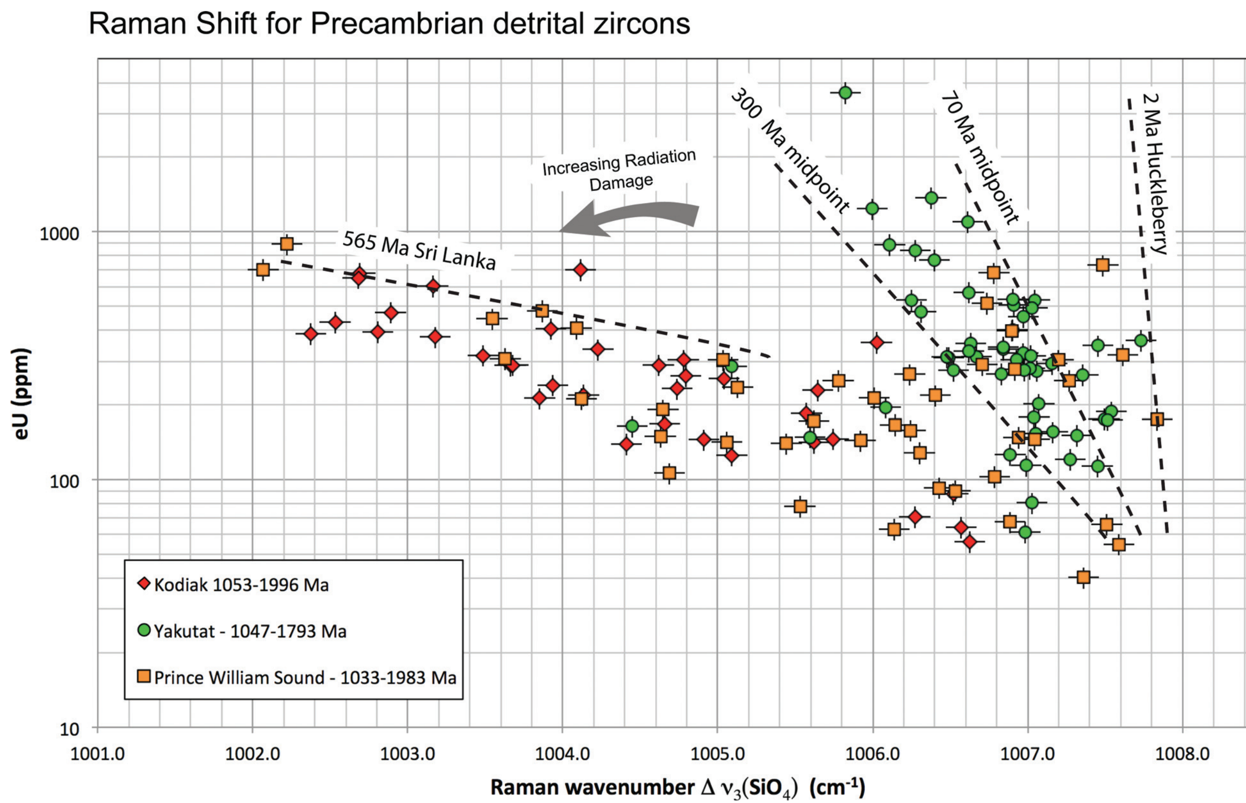

Fig. 4. Crystal disorder caused by internal radiation damage is shown here in the relationship between the position of a ν_3SiO_4 active mode and eU content in Precambrian zircon of the Chugach-Prince William terrane. The position of the ν_3SiO_4 mode shifts to lower wavenumbers with increasing radiation damage (Marsellos and Garver, 2010). In this case, the Western cohort of Precambrian grains shows considerable damage, more than the Sri Lankan (565 Ma) reference standard. The Eastern cohort is dominated by Precambrian grains that have a high degree of crystallinity, that appear to be more than our 70 Ma reference and less than our 300 Ma reference, both of which we think are quick-cooled volcanic grains. Thus the effective accumulation of radiation damage suggests that that Eastern cohort of Precambrian grains must have been derived from source rocks that were likely heated in the Jura-Cretaceous.

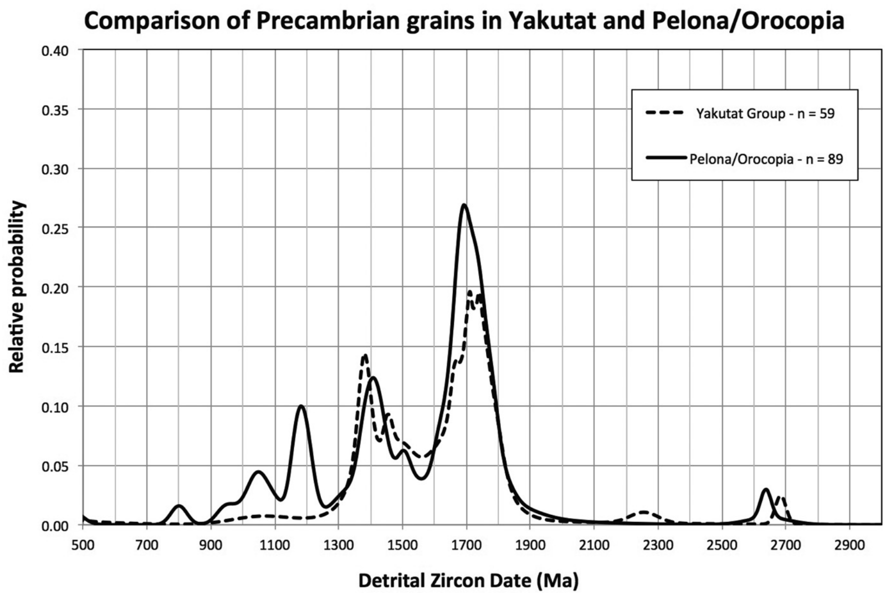

Fig. 5. Comparison of the grain-age distribution for Precambrian grains in the Yakutat Group (Alaska) and those of the schists of southern California (Pelona and Orocopia) (from Jacobson and others, 2011). Note that the two suites of zircon have a nearly identical grain age distribution that is characteristic of Yavapai- Mazatzal of Southwestern Laurentia, and a distinctive difference is the presence of Grenville zircons (~1.0–1.2 Ga in this case) in the schists of Southern California.

Sediment derived from this unique sediment pathway apparently spilled out into the forearc, and southwestern Laurentian zircons were delivered to Franciscan and Franciscan-like rocks that represent the accretionary complex in the forearc (Jacobson and others, 2011; Chapman and others, 2013). The Pelona-Orocopia-Rand (POR) schists of California are thought to be metamorphic equivalents of the Franciscan, and they are of interest because they also have southwestern Laurentian detrital zircons (fig. 5). The POR schists have a distinct diachronous depositional and metamorphic history and the inferred tectonic setting may be directly linked to tectonic erosion related to subduction of the Shatsky conjugate (Liu and others, 2010; Jacobson and others, 2011). It is possible that the Swakane Gneiss in the North Cascades of Washington has been displaced from this family of schists because it has a similar metamorphic history, and it too has zircons with southwestern Laurentian ages (Matzel and others, 2004; Jacobson and others, 2011).

In our analysis we assume that the Chugach-Prince William terrane is laterally continuous, and that these rocks were translated and moved together. An alternate hypothesis worth considering is that the Yakutat Group is not part of the Chugach terrane, and it has its own distinct history of accretion and translation that is independent from the rest of the CPW terrane (Bruns, 1980). The Yakutat Group includes an upper flysch facies and a lower mélange unit, which is Jurassic and or Early Cretaceous and it has correlatives on Baranof and Chicagof islands to the east (Plafker 1967; Plafker and others, 1994). The upper flysch facies in Yakutat Bay, which we sampled, is demonstrably Maastrichtian, and thus age correlative to the Sitka Graywacke to the east, and the Valdez Group, Kodiak Formation, and Shumagin Formation to the west (Plafker and others, 1994). Most detrital zircons in the Yakutat Group sample are similar to the correlative units across the belt as they support the inference that they were derived from an active Late Cretaceous arc and underlying metaplutonic complex. However, as discussed, the age distribution of the Precambrian grains differ dramatically. Early studies on sandstone composition across the belt revealed that sandstones of the Yakutat contain a slightly higher proportion of metamorphic grains and feldspar, but they are generally similar in composition (Zuffa and others, 1980). Detailed work on sandstones in Prince William Sound (to the west) shows that some units are compositionally similar and feldspar rich (Dumoulin, 1987). Future work should be directed at better understanding the relationship of the Yakutat Group to other age correlative units in the Chugach terrane and to age-correlative strata of the Nanaimo basin in southern British Columbia. This uncertainty does not invalidate our central hypothesis that the grain-age distribution, and isotopic signature of the detrital zircons from the Yakutat Group (eastern cohort) were derived from a unique and distinctive source in southwestern Laurentia that was exposed in the Late Cretaceous in southern California.

Translation Hypothesis

We hypothesize that the majority of the flysch on the CPW terrane accumulated in an accretionary complex flanking what is now the Coast Plutonic Complex (Farmer and others, 1993; Sample and Reid, 2003). This plutonic welt is dominated by Cretaceous and early Tertiary plutonic rocks and deeply exhumed metamorphic rocks (Gehrels and others, 2009). Basement terranes in this belt include rocks of the Yukon-Tanana terrane, which has a clear northern Laurentian Precambrian signature. We envision that in the Maastrichtian, the southern extent of this trench was in proximity to the Mojave breach in southern California, and thus part of the Chugach flysch shares a common history with part of the Franciscan Complex (fig. 6). Following deposition and accretion, much or most of these northbound terranes continued, or started, their coast-parallel journey north to Alaska. Erosional exhumation of the adjacent terranes and accretion continued during the entire journey. Geological relationships would suggest that most of this northward translation of the CPW occurred between 75 and 40 Ma. A clear and definitive tie can be made between the CPW and Wrangellia composite terrane in the Eocene, but prior to this their relationship and affinity is less certain (see Cowan, 2003).

The Baja British Columbia hypothesis reconciles paleomagnetic data and geologic observations from a number of units in the Wrangellia composite terrane and Coast Mountains orogen; a central tenant of this hypothesis is that these rocks were situated 3000 km to the south at 90 Ma (Cowan and others, 1997). The model requires significant coast-parallel translation between 90 and 50 Ma on the hypothetical Baja British Columbia fault and an intra-Quesnellia fault. The most outboard unit of the Wrangellia block is the Chugach-Prince William terrane and there is ample geologic evidence that collectively all of these terranes share a common history since 50 Ma when they are intruded by cross-cutting plutons. However, it is possible that before the Eocene, the flysch of the CPW was not associated with the Wrangellia block (and its outboard allies) and has a separate movement history because definitive geologic ties prior to this time have not been demonstrated. Note that here we question the long-assumed relationship between inboard Chugach terrane (McHugh complex, and other older units) and the more outboard flysch units of the Chugach and Prince William terranes, which are mainly Maastrichtian and younger.

If the southern end of the CPW was as far south as southern California, this hypothesis has important implications for Cordilleran geology, foremost among them is that the passage of this block of terranes coincides with cessation of magmatism in the Sierran Arc at ~80 Ma and it imposes a hiatus in subduction-accretion in Franciscan rocks. Our data suggest that the southern end of the Baja British Columbia block also included what is now the eastern part of the Chugach terrane, which has a

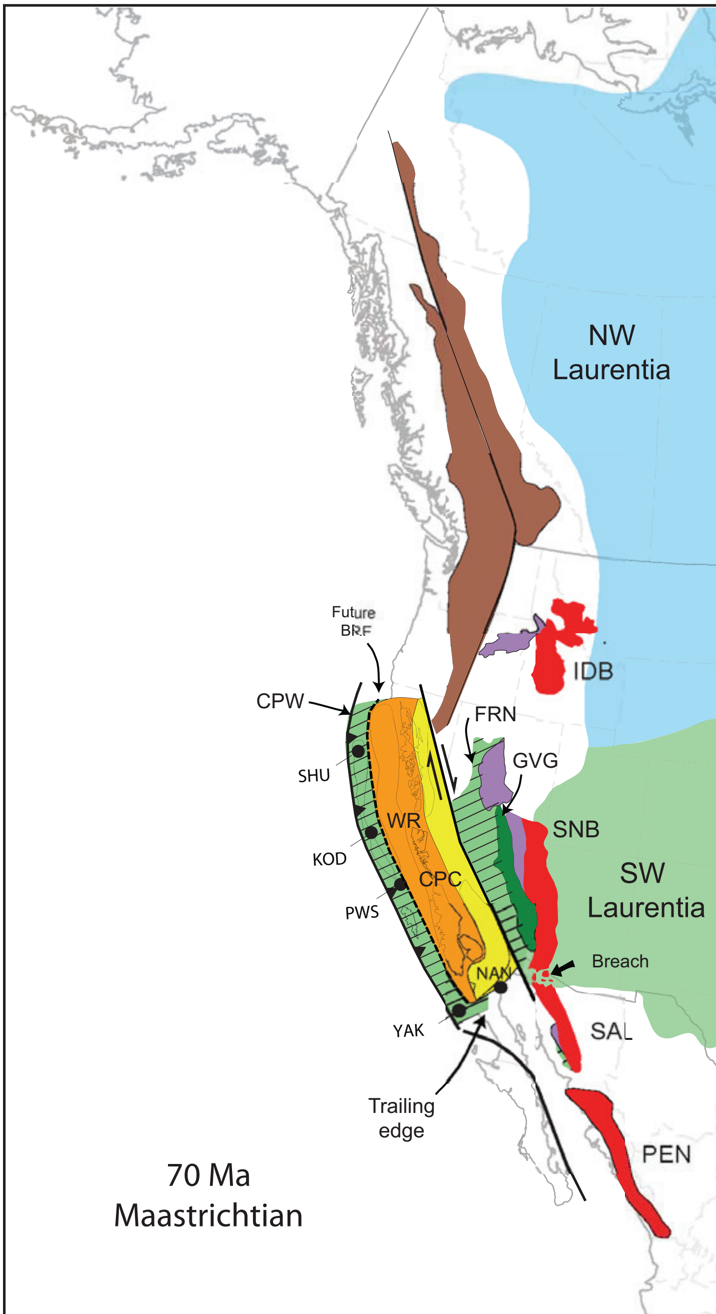

Fig. 6. Possible reconstruction for the Baja BC block at 70 Ma based on Cowan and others (1997) and Miller and others (2006). NW Laurentia includes areas underlain by a variety of Precambrian crustal elements that are mainly 1.8 Ga and older, and SW Laurentia is primarily underlain by the Yavapai, Mazaztal, and Grenville crustal provinces. Abbreviations used: [1] Cretaceous Arc and batholithic complexes: IDB – Idaho batholith; SNB – Sierra Nevada Batholith; SAL – Salinian block; PEN –Peninsular Ranges Batholith; CPC – Coast plutonic Complex (Cap – Plutonic). [2] Sedimentary basins and Accreted terranes: FRN – Franciscan Complex; GVG – Great Valley Group; WR – Wrangellia (s. lato). [3] Locations in the Chugach-Prince William flysch (CPC): SHU – Shugamins; KOD – Kodiak; PWS – Prince William Sound; YAK – Yakutat Bay; NAN – Nanaimo on southern Vancouver Island.

detrital zircon signature comparable to the rocks of the Franciscan Complex on the Nacimiento block (Chapman and others, 2013). Our reading of the requirements for translation would indicate that deposition occurred at 70 to 75 Ma at a latitude of southern California while translation was ongoing. By 50 Ma the eastern part of the Chugach was at a latitude comparable to the Pacific Northwest (Cowan, 2003).

The importance of long distance, margin-parallel transport of terranes in the Cordillera has long been postulated and debated (Coney and others, 1980; Monger and others, 1982; Cowan and others, 1997). In the case of the Baja British Columbia block, there are considerable paleomagnetic data from the CPW, basement elements of the Wrangellia composite terrane, and more inboard units of the Coast Mountains batholith that indicate offset of *ca.* 3000 km (see Cowan and others, 1997). However, there are also numerous observations of geologic connections across key terrane boundaries, and reasons why paleomagnetic data have been challenged (Butler and others, 2001; Hauessler and others, 2003). Cowan and others (1997) outlined mutually exclusive hypotheses for a southern option and a northern option for the Baja British Columbia block and then suggested several crucial tests that may be used to reject one option over the other. One of those tests involved the identification of unique sources of detrital zircons in sediments that can be derived from only one option, and not the other. We suggest that we have found such a distinctive source in the eastern CPW terrane, and parsimony suggests this subduction complex formed in southern California where they could have easily been derived from the southwestern corner of Laurentia. The occurrence of age and isotopically distinctive rocks of southwestern Laurentia, and the breach caused by tectonic erosion of the arc due to subduction of the Shatsky conjugate, effectively produced a Cordilleran piercing point in the Late Cretaceous. We suspect that a fuller understanding of the distribution of these sediments that contain distinct Precambrian zircons, and further characterization of their geochemical attributes, will lead to a better understanding of the paleogeography and construction of the North American Cordillera.

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APPENDIX A

U-Pb Geochronologic Analyses of Detrital Zircon from the Chugach-Prince William Terrane, Alaska

Zircon crystals were extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Samples are processed such that all zircons are retained in the final heavy mineral fraction. Two large splits of the sample (typically thousands of grains) are taken for U-Pb analysis. One split is set aside and the other is handpicked for Precambrian grains in ethanol under a binocular microscope. Grains are selected based on grain shape and color with the assumption that Precambrian grains are more likely to be well-rounded and display colors in the pink series due to the cumulative effects of radioactive decay (Garver and Kamp, 2002). The two splits are incorporated into a 1" epoxy mount together with fragments of our Sri Lanka standard zircon. The mounts are sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to isotopic analysis.

U-Pb geochronology of zircons is conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center (Gehrels and others, 2006, 2008). The analyses involve ablation of zircon with a Photon Machines Analyte G2 excimer laser (or, prior to May 2011, a New Wave UP193HE Excimer laser) using a spot diameter of 30 microns. The ablated material is carried in helium into the plasma source of a Nu HR ICPMS, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements are made in static mode, using Faraday detectors with $3x10^{11}$ ohm resistors for ^{238}U, ^{232}Th, ^{208}Pb-^{206}Pb, and discrete dynode ion counters for ^{204}Pb and ^{202}Hg. Ion yields are ~0.8 mv per ppm. Each analysis consists of one 15-second integration on peaks with the laser off (for backgrounds), 15 one-second integrations with the laser firing, and a 30 second delay to purge the previous sample and prepare for the next analysis. The ablation pit is ~15 microns in depth.

For each analysis, the errors in determining ^{206}Pb/^{238}U and ^{206}Pb/^{204}Pb result in a measurement error of ~1 to 2 percent (at 2-sigma level) in the ^{206}Pb/^{238}U age. The errors in measurement of ^{206}Pb/^{207}Pb and ^{206}Pb/^{204}Pb also result in ~1 to 2 percent (at 2-sigma level) uncertainty in age for grains that are >1.0 Ga, but are substantially larger for younger grains due to low intensity of the ^{207}Pb signal. For most analyses, the cross-over in precision of ^{206}Pb/^{238}U and ^{206}Pb/^{207}Pb ages occurs at ~1.0 Ga.

^{204}Hg interference with ^{204}Pb is accounted for measurement of ^{202}Hg during laser ablation and subtraction of ^{204}Hg according to the natural ^{202}Hg/^{204}Hg of 4.35. This Hg correction is not significant for most analyses because our Hg backgrounds are low (generally ~150 cps at mass 204).

Common Pb correction is accomplished by using the Hg-corrected ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers (1975). Uncertainties of 1.5 for ^{206}Pb/^{204}Pb and 0.3 for ^{207}Pb/^{204}Pb are applied to these compositional values based on the variation in Pb isotopic composition in modern crystal rocks.

Inter-element fractionation of Pb/U is generally ~5 percent, whereas apparent fractionation of Pb isotopes is generally <0.2 percent. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with known age of 563.5 ± 3.2 Ma (2-sigma error) is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1 to 2 percent (2-sigma) for both ^{206}Pb/^{207}Pb and ^{206}Pb/^{238}U ages.

Concentrations of U and Th are calibrated relative to our Sri Lanka zircon, which contains ~518 ppm of U and 68 ppm Th.

Notes for data table (Appendix table A; http://earth.geology.yale.edu/~ajs/SupplementaryData/2015/Garver):

1. Analyses with >10% uncertainty (1-sigma) in ^{206}Pb/^{238}U age are not included.
2. Analyses with >10% uncertainty (1-sigma) in ^{206}Pb/^{207}Pb age are not included, unless ^{206}Pb/^{238}U age is <500 Ma.
3. Best age is determined from ^{206}Pb/^{238}U age for analyses with ^{206}Pb/^{238}U age <1000 Ma and from ^{206}Pb/^{207}Pb age for analyses with ^{206}Pb/^{238}Uage > 1000 Ma.
4. Concordance is based on ^{206}Pb/^{238}U age/^{206}Pb/^{207}Pb age. Value is not reported for ^{206}Pb/^{238}U ages ^{206}Pb/^{207}Pb age.
5. Analyses with ^{206}Pb/^{238}U age > 500 Ma and with >20% discordance (<80% concordance) are not included.
6. Analyses with ^{206}Pb/^{238}U age > 500 Ma and with >5% reverse discordance (<105% concordance) are not included.
7. All uncertainties are reported at the 1-sigma level, and include only measurement errors.
8. Analyses conducted by LA-MC-ICPMS, as described by Gehrels and others (2008).
9. U concentration and U/Th are calibrated relative to Sri Lanka zircon standard and are accurate to ~20%.
10. Common Pb correction is from measured ^{204}Pb with common Pb composition interpreted from Stacey and Kramers (1975).
11. Common Pb composition assigned uncertainties of 1.5 for ^{206}Pb/^{204}Pb, 0.3 for ^{207}Pb/^{204}Pb, and 2.0 for ^{208}Pb/^{204}Pb.
12. U/Pb and ^{206}Pb/^{207}Pb fractionation is calibrated relative to fragments of a large Sri Lanka zircon of 563.5 ± 3.2 Ma (2-sigma).
13. U decay constants and composition as follows: ^{235}U = 9.8485 × 10-10, ^{238}U = 1.55125 × 10-10, ^{238}U/235U = 137.88.

APPENDIX B

Hf Isotopic Data from the Chugach-Prince William Terrane, Alaska

Analytical methods at the Arizona LaserChron Center.—Hf isotope analyses are conducted with a Nu HR ICPMS connected to a New Wave UP193HE laser (2009-2010) or a Photon Machines Analyte G2 excimer laser (2011). Instrument settings are established first by analysis of 10 ppb solutions of JMC475 and a Spex Hf solution, and then by analysis of 10 ppb solutions containing Spex Hf, Yb, and Lu. The mixtures range in concentration of Yb and Lu, with ^{176}(Yb+Lu) up to 70 percent of the ^{176}Hf. When all solutions yield ^{176}Hf/^{177}Hf of ~0.28216, instrument settings are optimized for laser ablation analyses and seven different standard zircons (Mud Tank, 91500, Temora, R33, FC52, Plesovice, and Sri Lanka) are analyzed. These standards are included with unknowns on the same epoxy mounts. When precision and accuracy are acceptable, unknowns are analyzed using exactly the same acquisition parameters.

Laser ablation analyses are conducted with a laser beam diameter of 40 microns, with the ablation pits located on top of the U-Pb analysis pits. CL images are used to ensure that the ablation pits do not overlap multiple age domains or inclusions. Each acquisition consists of one 40-second integration on backgrounds (on peaks with no laser firing) followed by 60 one-second integrations with the laser firing. Using a typical laser fluence of ~5 J/cm2 and pulse rate of 7 hz, the ablation rate is ~0.8 microns per second. Each standard is analyzed once for every ~20 unknowns.

Isotope fractionation is accounted for using the method of Woodhead and others (2004): βHf is determined from the measured ^{179}Hf/^{177}Hf; βYb is determined from the measured ^{173}Yb/^{171}Yb (except for very low Yb signals); βLu is assumed to be the same as βYb; and an exponential formula is used for fractionation correction. Yb and Lu interferences are corrected by measurement of ^{176}Yb/^{171}Yb and ^{176}Lu/^{175}Lu (respectively), as advocated by Woodhead and others (2004). Critical isotope ratios are ^{179}Hf/^{177}Hf =0.73250 (Patchett and Tatsumoto, 1980); ^{173}Yb/^{171}Yb = 1.132338 (Vervoort and others, 2004); ^{176}Yb/^{171}Yb =0.901691 (Vervoort and others, 2004; Amelin and Davis, 2005); ^{176}Lu/^{175}Lu = 0.02653 (Patchett, 1983). All corrections are done line-by-line. For very low Yb signals, βHf is used for fractionation of Yb isotopes. The corrected ^{176}Hf/^{177}Hf values are filtered for outliers (2-sigma filter), and the average and standard error are calculated from the resulting ~58 integrations. There is no capability to use only a portion of the acquired data.

All solutions, standards, and unknowns analyzed during a session are reduced together. The cutoff for using βHf versus βYb is determined by monitoring the average offset of the standards from their known values, and the cutoff is set at the minimum offset. For most data sets, this is achieved at ~6 mv of ^{171}Yb. For sessions in which the standards yield ^{176}Hf/^{177}Hf values that are shifted consistently from the known values, a correction factor is applied to the ^{176}Hf/^{177}Hf of all standards and unknowns. This correction factor, which is not necessary for most sessions, averages 1 epsilon unit.

The ^{176}Hf/^{177}Hf at time of crystallization is calculated from measurement of present-day ^{176}Hf/^{177}Hf and ^{176}Lu/^{177}Hf, using the decay constant of ^{176}Lu (λ = 1.867e^{-11}) from Scherer and others (2001) and Söderlund and others (2004). No capability is provided for calculating Hf Depleted Mantle model ages because the ^{176}Hf/^{177}Hf and ^{176}Lu/^{177}Hf of the source material(s) from which the zircon crystallized is not known.

Notes for table B, http://earth.geology.yale.edu/~ajs/SupplementaryData/2015/Garver:

1. Data reduction methodology is from Woodhead and others (2004)
2. Analytical methods described in detail by Gehrels and Pecha (2014)
3. (^{176}Yb + ^{176}Lu)/^{176}Hf (%) expresses the proportion of 176 due to ^{176}Yb + ^{176}Lu versus the proportion due to ^{176}Hf, in %.
4. Volts Hf is the sum of voltages of all Hf isotopes.
5. ^{176}Hf/^{177}Hf is the measured ^{176}Hf/^{177}Hf, corrected for fractionation and interfences. Shown with uncertainty expressed at 1-sigma.
6. ^{176}Lu/^{177}Hf is the intensity of ^{176}Lu, calculated from the measured instensity of ^{175}Lu and ^{176}Lu/^{175}Lu=0.02653 (from Patchett, 1983), compared to the measured intensity of ^{177}Hf. Fractionation of Lu isotopes is assumed to be the same as fractionation of Yb isotopes.
7. ^{176}Hf/^{177}Hf (T) is the ^{176}Hf/^{177}Hf corrected to the time of crystallization using a decay constant of 1.867e-11 (from Scherer and others, 2001 and Soderland and others, 2004)
8. E-Hf (0) is the present-day epsilon Hf value using ^{176}Hf/^{177}Hf=0.282785 and ^{176}Lu/^{177}Hf=0.0336 (from Bouvier and others, 2008). The uncertainty is expressed at 1-sigma.
9. E-Hf (T) is the epsilon Hf value at the time of crystallization. The uncertainty is expressed at 1-sigma.
10. U-Pb ages are based on 206/238 for ages younger than ~1.0 Ga, and on 206/207 for ages older than ~1.0 Ga. This age cutoff may be slightly different for each sample.
11. Isotope ratios as follows:

180/177 1.8866600 Patchett (1983)
179/177 0.7325000 Patchett and Tatsumoto (1980)
178/177 1.4671800 Patchett (1983)
176/177 0.2821600 Patchett (1983)
174/177 0.0087100 Patchett (1983)
176/175 0.0265300 Patchett (1983)
176/171 0.9016910 Vervoort and others (2004)
173/171 1.1323569 Vervoort and others (2004)
172/171 1.5317360 Vervoort and others (2004)

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