Tectonic Evolution of the Chugach-Prince William Terrane: U/Pb Detrital Zircon Age and Provenance of Cover Strata to the Paleocene Resurrection Peninsula Ophiolite in Seward, Alaska

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Geology Honors Thesis, B.S.
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Abstract

The southern margin of Alaska is defined by a late Mesozoic to Cenozoic accretionary complex that comprises the Upper Cretaceous to Eocene Chugach-Prince William (CPW) terrane. The Contact Fault serves as the current boundary between the Upper Cretaceous Valdez Group of the Chugach terrane and the Paleocene to Eocene Orca Group of the Prince William terrane. However, sandstones of the Campaniam-Maastrichtian Valdez Group and the Paleocene Orca Group consist of compositionally indistinguishable feldspathic and volcanic-lithic sandstones thereby hindering the identification and fault bounding the two terranes.

During the Paleocene to early Eocene, ridge subduction led to the formation and emplacement of the Resurrection and Knight Island ophiolites and subsequent intrusion of the Sanak-Baranof belt (SBB) plutons along the 2200 km length of the CPW accretionary complex. Controversy surrounds the age of the ophiolites and the age and stratigraphic relationship of adjacent clastic strata. On the northeastern side of Resurrection Peninsula, a thrust fault is mapped between the ophiolite and Upper Cretaceous Valdez Group. However, on the western side, there is controversy about the stratigraphic affinity of clastic strata . The crux of the issue being whether the strata are Cretaceous Valdez Group and fault bounded bearing no direct relationship to the ophiolite, or whether they are Paleocene Orca Group and essentially in stratigraphic continuity with the ophiolite.

To distinguish between the Chugach and Prince William terrane and determine the age, provenance and stratigraphic affinity of the clastic rocks interbedded with (and stratigraphically above) the Resurrection Peninsula Ophiolite, U/Pb detrital zircon dates were collected from four samples (n=404) within the Resurrection Bay area. The grain age distributions from Resurrection Bay were compared with previous U/Pb detrital zircon ages obtained from strata of the Chugach terrane and Prince William terrane. All samples from Resurrection Bay were correlative to the Orca Group in the Prince William terrane that indicates the ophiolite is in depositional continuity and part of the CPW accretionary complex. These results validate previously collected paleomagnetic data obtained from the Resurrection Peninsula ophiolite that indicate a paleolatitude 13 ± 9° south of the present location to near present day northern Washington. Together, these results support large coast parallel transport of the CPW terrane since the Paleocene and the search for the original source of the clastic rocks may include terrains to the south.

Introduction

The southern margin of Alaska exposes a late Mesozoic to Cenozoic 30 km thick accretionary complex (Fig.1) that comprises the Chugach and Prince William (CPW) terranes (Fig.2). During the Paleocene to early Eocene, ridge subduction at a trench-ridge-trench (T-R-T) boundary led to the formation and emplacement of ophiolitic sequences, including the Resurrection and Knight Island ophiolites, and subsequent migrating intrusion of the Sanak-Baranof belt (SBB) plutons along the 2200 km length of the CPW (Fig.2). The CPW terranes young in the outboard direction starting with the Chugach terrane, composed of the Late Jurassic to Late Cretaceous McHugh Complex and the Upper Cretaceous Valdez Group, and the Prince William terrane, made up of the Paleocene to Eocene Orca Group. The Contact Fault separates the Valdez Group and Resurrection Peninsula ophiolite from the Orca Group and the Knight Island Ophiolite and thus serves as the interpreted boundary between the Chugach and Prince William terranes in the Kenai Peninsula and western Prince William Sound area (Fig.3). The Valdez Group and Orca Group are dominated by deep marine flysch sequences (Fig.4) with a thick to thin bedded turbidic sandstone base that fines upward into thin interbedded shales and mudstones containing little to no fossil assemblages. Sandstones of the Valdez Group and the Orca Group consist of lithologically similar feldspathic and volcanic-lithic sandstones that indicate a magmatic arc source (Dumoulin, 1987). No definitive contact has been observed between the Valdez and Orca Group, due to the sparse supply of age-defining paleontological data (Plafker, 1985) and the lack of corroborative indicators such as deformation, change in metamorphic grades, or stratigraphic breaks. Therefore the present boundary, the Contact Fault, was ambiguously drawn in to separate the Late Jurassic to Cretaceous Chugach and Paleocene to Eocene Prince William terranes.

Dumoulin (1987) conducted extensive petrographic analysis to resolve this question, studying 950 samples of sandstones from the Valdez and Orca Groups and performing additional point count analysis on 111 samples. Dumoulin concluded that the clastic compositions do not support a boundary separating two different terranes but rather indicate a single unbounded terrane of continuously deposited flysch sequences (Fig.5). However, since Dumoulin’s study, additional isotopic analysis has provided diagnostic tools to distinguish the Chugach and Prince William terranes. Subsequent geochronology on samples from both the Valdez (Amato and Pavlis, 2011; Kochelek et al., 2011) and Orca Groups (Hilbert-Wolf, 2012) demonstrate two unique detrital zircon U/Pb signals that allow the two units, and thus terranes, to be distinguished.

In this study, I contribute new U/Pb detrital zircon data from the Valdez and Orca Groups to determine the boundary between the Chugach and Prince William terrane by exploiting their diagnostic grain age distributions (Fig.6). The distinct detrital signals have also proven pivotal in establishing the relationship between the Resurrection Peninsula and Knight Island ophiolites and the Chugach-Prince William accretionary complex. Presently, controversy surrounds the age of the ophiolites and the age and stratigraphic relationship of adjacent clastic strata (see Bradley and Miller, 2006). Original mapping of the Resurrection Ophiolite indicated it was associated with the Cretaceous Valdez Group, and hence was thought to be Cretaceous in age (Tysdal and Case, 1979). A U/Pb zircon date from an intrusive plagiogranite from Killer Bay on the east side of the Resurrection Peninsula constrains the age of the ophiolite at 57 ± 1 Ma; the Knight Island Ophiolite (in

Prince William Sound) is undated but assumed to be the same age (Nelson et al., 1989). On the northeastern side of Resurrection Peninsula, a thrust fault is mapped between the ophiolite and Upper Cretaceous Valdez Group. However, on the western side, there is controversy about the stratigraphic affinity of clastic strata (cf. Bradley and Miller, 2006; Kusky and Young, 2004), with the crux of the issue as to whether the strata are Cretaceous Valdez Group and fault bounded, or whether they are Paleocene Orca Group and essentially in stratigraphic continuity with the ophiolite (Fig.6). To determine the age, provenance and stratigraphic affinity of the clastic rocks interbedded with and stratigraphically above the Resurrection Peninsula Ophiolite, U/Pb detrital zircon dates were obtained from four samples (n=404) within the Resurrection Peninsula area (Fig.7). One sample (RB12-04, is from a thin-bedded, medium-grained sandstone interbedded with (and cross- cut by) basaltic rocks and thus this sample provides a key tie to the ophiolite. The purpose of this paper is to use U/Pb ages of detrital zircons in order to resolve the boundary between the Upper Cretaceous Valdez of the Chugach terrane and Paleocene to Eocene Orca of the Prince William terrane. By distinguishing the locations of the two ages, the debated relationship of the Resurrection Peninsula and corresponding Knight Island ophiolites with the accretionary complex can be determined. If the ophiolites are in fact part of the accretionary complex, then previous paleomagnetic data taken from both areas are validated and apply to the entire CPW terrane. As it stands, both locations paleomagnetic results indicate Early Paleocene paleolatitudes more than 1000 km south of present locations.

Geologic Background and Setting

Terrane Tectonics

Discrete crustal blocks with varying geologic ages exist along the western margin of North America and southern margin of Alaska. In order to explain their existence, various models developed into what is now referred to as terrane tectonics (e.g., Ridgway and Flesch, 2007). A terrane is defined as a geologically distinct, fault-bounded, crustal block that has no relationship to adjacent rock. Terranes form at one location before undergoing translation to their present day positions. This idea was initially formulated to explain the tectonics responsible for the accreted assemblages surrounding and cross-cutting what is now referred to as the Wrangellia composite terrane in southern Alaska (Jones et al., 1977). Two possible explanations exist that differ in the tectonic processes responsible for translating and accreting the terranes to the continental margin: the terrane tectonics model (Ridgway and Flesch, 2007) and the extrusion model (Redfield et. al 2007). The generally accepted terrane tectonics model proposes that these exotic crustal land masses move passively along with oceanic crust experiencing slab pull forces associated with subduction. Eventually, the terrane reaches the subduction zone but, due to its lower density, the buoyant terrane does not subduct. Instead, the terrane forces the subduction zone to move out at which point it is amalgamated to the overlying plate of the continental margin (Ridgway, 2007). The extrusion model compares the terranes along the southern Alaskan margin to crustal rafts that flow along what is termed the North Pacific Rim orogenic stream (NPRS) (Redfield et. al, 2007). Once the terranes are accreted to the strike-slip plate boundary, they are laterally transported until encountering the Alaska orocline. At this point, the terranes northward movement is hindered and their path is diverted or extruded southwestward toward the Aleutian-Bering Sea subduction zone (Redfield et. al, 2007).

Southern Composite Terrane

The Mesozoic to Cenozoic Southern Margin composite terrane is separated to the north from the Paleozoic to Mesozoic Wrangellia composite terrane by the Border Ranges strike-slip fault and to the south from the Pacific plate by the Aleutian mega thrust system (Fig. 9). The Southern Margin is comprised of the St. Elias, Ghost Rocks, Chugach, Prince William terranes and the actively colliding Yakutat terrane (Plafker et. al 1994). Since the Oligocene, the Yakutat terrane has undergone northward translation along the Fairweather right-lateral strike-slip fault. Around 10 Ma, the Yakutat terrane collided with the Aleutian trench and began the oblique subduction observed in the present day Gulf of Alaska coast (Enkelmann et al, 2013). The tectonic evolution of the Yakutat terrane thus coincides with the extrusion model proposed by Redfield (2007) that supports the application of lateral translation to other terranes within the Southern Margin composite terrane including the Chugach and Prince William terranes.

Chugach-Prince William Terrane

The Chugach-Prince William terrane (Fig.2) represents what is believed to be one of the largest subduction related accretionary complexes in the world (Plafker, 1994). The beginning of its formation is indicated by metamorphic blueschist facies that support subduction beginning in the Mesozoic (Bradley et al., 1999) until the Cenozoic resulting in the 30 kilometer thick, 20 km wide accretionary wedge of the Chugach-Prince William terrane. During the Paleocene to early Eocene, ridge subduction occurred at a trench-ridge-trench (T-R-T) boundary. The interaction of a slab free region or slab window with the overlying accretionary wedge led to the formation and emplacement of the Resurrection and Knight Island ophiolites and subsequent migrating intrusion of the Sanak-Baranof belt (SBB) plutons that expand the entire length of the CPW (Fig.2). However, competing hypothesis (i.e. Cowan, 2003; Haeussler et al., 2003) propose varying plate geometry models for the trench-ridge-trench boundary that suggest two different possible locations of the CPW terrane prior to 50 Ma: one that is more or less in place, and one that places it south along the continental margin near Seattle or Vancouver (Fig.10). Previously published paleomagnetic data from the Resurrection and Knight Island ophiolites indicate that prior to ophiolite formation, the CPW terrane laid 1100 kilometers south of its present location (Bol et. al., 1992). Presently, the paleomagnetic results have not gained wide acceptance due to ambiguities in the relationship between the ophiolite and the flysch of CPW accretionary complex and due to structural complexity.

The Chugach Terrane

The Chugach terrane ranges from 60-100 km wide (Plafker et al., 1994) and expands 2200 km along the southern margin of Alaska from the Sanak and Shumagin Islands in the southwest tip to Baranof Island towards the southeast (Fig.2; Cowan, 2003). The Chugach terrane is bounded from the mid to late Jurassic Peninsular terrane by the Border Range's strike-slip fault and from the Paleocene to Eocene Prince William terrane by the Contact thrust Fault. Within the Chugach terrane outcrops the Jurassic to Late

Cretaceous (Nelson et al., 1986) McHugh Complex, the Upper Cretaceous Valdez Group, and Paleocene to Eocene near-trench volcanic rocks, plutons, and ore deposits (Fig.12). The mafic and ultramafic volcanic rocks that comprise the Resurrection Peninsula ophiolite are accreted to south-central margin of the Chugach terrane in Resurrection Bay, Seward, Alaska. The ophiolite and accompanied sulfide deposits are associated with a subducting spreading ridge (Bradley et. al 2003). The sediment adjacent to the ophiolite is currently mapped to the left of the Contact Fault boundary as part of the Upper Cretaceous Valdez Group of the Chugach terrane thus separating it from the younger Prince William terrane (Fig.3). The dikes to batholith sized plutonic rocks intrude the Chugach Terrane along strike but in a unique age progressive pattern. The forearc magmatism has been interpreted as a migrating slab window generated from a subducted ridge. The window's path, based on geochronologic data (Bradley et al., 2003), begins at 61 Ma in the southwest Sanak Islands to 50 Ma in the southeast Baranof Island. The extent of the intrusions is reflected in its official name: the Sanak Baranof Belt (Hudson et al., 1979).

McHugh Complex

The McHugh complex is defined as an inchoate, Late Triassic to Early Cretaceous mélange assemblage formed during the early stages of subduction. It preserves the initial formation of the accretionary complex and as such defines the northern margin of the Chugach terrane. The McHugh is fault bounded on either side, with the Border Ranges fault separating it from the older Peninsular terrane (part of the Wrangellia composite terrane) and the Eagle River thrust fault separating it from the Upper Cretaceous Valdez Group (Fig.12). The mélange assemblage contains highly deformed and metamorphosed basalts, tuff, chert, argillite, siltstone, carbonates, and greywacke sandstone. Results from U/Pb detrital zircon ages caused Amato and Pavlis (2010) to divide the McHugh Complex into two units based on differing lithologies, times of accretion, and arc sources. The first, a mesomélange unit, is defined by metavolcanic N-MORB basalts and sheared, recrystallized argillite enclosing disrupted beds of chert (Plafker et al., 1994; Amato and Pavlis, 2010). Two samples from this unit revealed maximum depositional ages of 157 ± 3 Ma and 146 ± 5 Ma. Based upon U/Pb, radiolarian, and intrusion ages, the older McHugh is believed to represent an older time of accretion. Its timing is consistent with active magmatism in the Chitina and Talkeetna arcs on the Wrangellia composite terrane that provide a potential primary source (Amato and Pavlis, 2010). The second, a greywacke conglomerate unit, is distinguished by matrix supported conglomerates and massive, tens of meters thick, volcaniclastic greywacke (Plafker et al., 1994; Amato and Pavlis, 2010). Six samples from this unit revealed maximum depositional ages ranging from 91 to 84 Ma. These Cretaceous aged zircons coincide with the timing and location of the Coast Orogen believed to be the probable source for the younger McHugh and Valdez Groups. Though no Precambrian or Paleozoic grains were found in the older mesomélange unit, seven were found in the younger greywacke unit providing further evidence for an alternate source. Amato and Pavlis (2010) conclude that the younger zircon ages best approximate the timing of accretion due to rapid arc to trench deposition and evidence for a local arc source.

Valdez Group

The Late Cretaceous, Campanian to Maastrichtian aged Valdez Group comprises the majority of the Chugach terrane and the most coherent section of the accretionary complex that extends for over 2000 km along the southern Alaskan margin. The Eagle River thrust fault serves as the upper boundary separating the Late Cretaceous Valdez Group from the Late Jurassic McHugh Complex (Fig.12). The Valdez Group is believed to have been deposited in a deep sea trench that, based on paleocurrent measurements, experienced westward current movements (Nilsen and Zuffa, 1982). Though volcanic basalts occur in sparse amounts, the bulk of the Valdez Group is comprised of episodic, deep marine flysch sequences (Fig.4). Notable features of the flysch sequences include their monotony across 2200 km and thicknesses between 10 and 20 km (Plafker et al., 1994) that pervade the Chugach and Prince William terranes. The flysch deposits indicate slope, fan, and basin-plain marine environments (Dumoulin 1974) conducive to graded bedding. The base of the sequence consists of thin to thick bedded turbidic sandstones that fine upward into thin bedded sandstones, shales, siltstone, and interbeded mudstones. Flysch sequences to the west of the Chugach Mountains have experienced low grade metamorphism indicated by zeolite to prehnite-pumpellyite facies as well as slaty and crenulated cleavage. The flysch sequences have also undergone intensive deformation evident in complex folding and faulting supported by boudins and mylonitic shear zones.

Extensive petrographic studies on twenty-nine samples from Valdez sandstones were conducted by Dumoulin (1974). Dumoulin found samples contain poor to well sorted grains with a 10-20% recrystallized clay matrix. Samples contained large volumes of volcanic lithic fragments with lathwork textures, quartzofeldspathic grains, sedimentary lithic fragments, and noticeable amounts of slate and phyllite metamorphic lithic fragments (Fig.5). Based upon the abundance of volcanic clasts and scarce amounts of quartzose grains, Dumoulin concludes a predominately magmatic arc source for the Valdez sandstone.

Previous U/Pb detrital zircon ages from four turbidite samples of the Valdez Group were obtained by Kochelek et al. (2011). Two samples were obtained from an area north of Anchorage near Mount Magnificent. Results from these samples yielded older grain populations with a maximum depositional age (from an average of the seven youngest grains) of 82 ± 3 Ma that fits with the Late Cretaceous age yielded by 30% of the grain population. However, 46% of the grains analyzed revealed a Triassic-Jurassic aged population. Results from the three samples that were collected further outboard along a fifty-kilometer transect south of Anchorage, Alaska had maximum depositional ages (based on the 3-7 youngest grains) between 67 and 68 Ma. Two of the other samples collected further inboard of the terrane contained older grain populations with maximum depositional ages between 82-81 Ma. Kochelek et al. (2011) determined that eroded grains from the Coast Orogen are the most probable source for the Late Cretaceous grain populations of the Valdez Group. Since no significant age gap exists between the later McHugh Complex and the adjacent earlier Valdez Group, continuous deposition occurred with a change in depositional style. Kochelek et al. (2011) believe the McHugh complex indicates sediment filled the trench around 84 Ma. The subsequent deposition of the Valdez Group onto the oceanic plate is consistent with the observed thick coherent flysch sequences that comprise the bulk of the CPW.

Prince-William Terrane

The Prince-William terrane constitutes the furthest outboard terrane indicating the final stages of accretion that occurred during Paleocene to Eocene subduction. Prince-William terrane includes early Eocene Ghost Rocks (Plumley, 1984) and Sitkalidak Formation of the Kodiak Islands, Late Paleocene to Eocene Orca Group within Prince William Sound, and Paleocene to Eocene volcanic rocks including the Resurrection and Knight Island ophiolites (Fig.3). Currently, the Contact Fault denotes the lower boundary between the Upper Cretaceous Valdez Group of the Chugach terrane and the Paleocene to Eocene Orca Group of the Prince William terrane. The Contact Fault is well exposed in the northern and more eastern areas of the Prince-William terrane where thrust fault surface exposure and signs of deformation including metamorphic textures and index minerals have been observed. Within these areas, the fault separates the Valdez Group from the Ghost Rocks Formation in the Kodiak Islands as well as juxtaposes the Eocene Ghost Rocks with the older Kodiak Formation. However, in the more western regions of Prince William Sound, the Contact Fault is mapped by approximation due to no observed deformation or significant changes in metamorphic grade, structure, and lithology between the Valdez Group and the Orca Group (Dumoulin, 1987). Dumoulin addresses the issue by conducting compositional analyses between the Valdez and Orca Groups in order to isolate a possible diagnostic characteristic. Determining the difference between the two groups would allow further definition between the Chugach and Prince William terranes as well as provide a foundation for the Contact fault placement.

Ghost Rocks Formation

The Ghost Rocks Formation outcrops in the southeastern region of the Kodiak Islands that are fault bounded to the north from Upper Cretaceous rocks of the Kodiak Formation and to the south from the Eocene aged Sitkalidak Formation (Fig.13). The Ghost Rocks Formation is a 160 km expanse of deformed, medium to thick bedded turbidic and argillitic sandstones interbedded with basaltic and andesitic volcanic rocks that are also interbedded with pelagic limestone (Gallen, 2008; Plafker et al., 1994). The Ghost Rocks Formation also shares unique geologic characteristics with the Resurrection Peninsula ophiolite that contribute to the generally accepted beliefs that both formed in a trench-ridge-trench setting from ridge subduction. The lithologic and relational similarities include volcaniclastic sediments interbedded with pillow basalts, volcanic breccia, mafic dikes, and other igneous intrusions that yield a predominately MORB signature (Gallen, 2008). The Ghost Rocks were at one time affiliated with the Resurrection Peninsula ophiolite sequence (Jones et al., 1987). This interpretation was later refuted based upon a U/Pb detrital zircon age of 57 Ma ascribed to the ophiolite, thus making it too young for the Ghost Rocks Formation whose Late Cretaceous to Paleocene age is based upon planktonic fossil assemblages (Plafker et al., 1994). However, recent ^{40}Ar/^{39}Ar on an intrusive pluton yielded an age of 60.15 ±0.86 Ma (Farris et al., 2006) that, with two other previously published isotopic data of plutons, constrains the maximum depositional age of the Ghost Rocks Formation between 60-63 Ma (Gallen, 2008).

Two separate paleomagnetic studies have been conducted on the Ghost Rocks Formation in the Kodiak Islands (Plumley et. al, 1983; O'Connell et al., 2007; Gallen, 2008), with a focus on Alitak Bay and 80 km west at Kiliuda Bay within the formation. The initial study was conducted by Plumley et al. (1982, 1983), who collected paleomagnetic data from pillow lavas at the two above localities. Of the two localities, 187 cores were taken from a tuff unit and 28 from basaltic and andesitic lava flow deposits. Based on results from fold tests, reverse polarity tests, and structural relations, the remanent magnetization was acquired during the initial cooling and crystallization of the lava flows. Structural corrections to the paleohorizontal yielded a 122º variation in declination measurements of mean primary directions between lava flows of Kiliuda Bay and those of Alitak Bay but only a 12º variation in mean inclination (Plumley et al., 1982, 1983). Despite these significant differences, the two areas are within the same formation and along strike. As such, Plumley believes they record the same inclination of remanent magnetization. The paleomagnetic results were then combined from the two areas in order to obtain a representative paleolatitude of the Ghost Rocks Formation 60-65 Ma years ago. The mean inclination found (40±6°) was much shallower than the expected paleolatitude of the current location (68±5°) and indicate a northward translation of 25±7° or ~3000 km since the Early Paleocene (60-65 Ma).

A paleomagnetic study conducted by Gallen (2008) in collaboration with O'Connell et al. (2007) , expanded on by Plumley (1982, 1983) by increasing the number of samples and broadening their localities and lithologies for paleomagnetic data. The study aimed to correct for the discrepancies between the two sample sites (Alitak Bay and Kiliuda) published by Plumley et al. (1983). Gallen incorporated 176 samples sites at four localities that included the same previous areas of Alitak and Kiliuda Bay as well as expanded the area to include Jap Bay. Three hundred cores in Jap Bay and 500 cores from Alitak Bay were collected with lithologies ranging from sedimentary rocks, conglomerates, volcanic flows, plutons, and volcanic breccia. Gallen reports paleolatitudes of 41°±8° that suggest the Ghost Rocks Formation experienced over 1500 km of translation from the Paleocene to the present.

Orca Group

The Paleocene to Eocene Orca Group flysch embodies the Prince William terrane and covers over 21,000 km^2 of land area. The Orca Group is north-bounded from the Valdez Group of the Chugach terrane by the Contact Fault and south-bounded from the Yakutat terrane by the Chugach-St. Elias fault (Fig.12). The Orca Group contains lithologies very similar if not indistinguishable from the Upper Cretaceous Valdez Group in addition to nearly complete ophiolitic sequences sporadically exposed along a roughly 150 km transect in the Gulf of Alaska.

The main ophiolite sequences include the Resurrection Peninsula ophiolite (Fig.7, 14, 16a and b) and Knight Island ophiolite. The ophiolites are believed to be related and Orca-aged based upon pillow basalts within the sequences that are interbedded with deep marine flysch-sequences of clastic turbidic sands with reverse grading of thin to thick bedded sands indicating distance from the continental margin (Kusky and Young, 1999). As observed in the Valdez Group, complex folding and faulting record intense deformation in the Orca Group. The Orca has also experienced similar low grade metamorphism indicated by prehnite-pumpellyite to lower greenschist metamorphic facies (Dumoulin, 1977). Until recently, the older age of the Orca was tentatively constrained based on Paleocene fossil assemblages observed at a single locality including gastropods, pelecypods, and crabs (Plafker et al., 1985). Additional isotopic has constrained the younger Eocene Orca age from plutons that intrude the northern belts of the Orca Group (Plafker and Lanphere, 1974). Uncertainties in the age persist from failings in the paleontological data to constrain the older ages of the Orca and in the isotopic data to constrain younger ages of outboard belts not intruded by plutons (Plafker et al., 1985).

Thorough petrographic studies were conducted by Dumoulin (1977) on eighty-three sandstone samples from various localities within the Orca Group. Dumoulin found that there were significant compositional differences between the further inboard samples including the Sargent Ice field, Chenega, and Ghost Rocks Formation and the more southern outboard samples including Montague Island, Ragged Mountain, and the Sitkalidak Formation of Prince William Sound (Fig.3). Dumoulin inferred that the more southern outboard samples could represent a separate belt of younger rocks that accreted later. Dumoulin also concluded that significant changes did not occur across the Contact Fault between the eastern Valdez Group of the Chugach and the western Orca Group of Prince William Sound. Rather, both groups exhibit gradual increases in quartz, plagioclase, and potassium feldspar moving eastward in the younging direction of the accretionary complex. The presence of a fault, therefore, is not evident in the petrographic analysis across the currently mapped boundary separating the Valdez and Orca groups.

Though no significant composition change was found between Valdez and Orca sandstones, there were changes in composition within samples from the Orca Group. Dumoulin considered these and their locations near mapped faults when investigating possible locations of a terrane boundary including the Johnstone Bay Fault, Placer River Fault, Bainbridge Fault, and Montague Strait Fault. The latter two of these are included in structurally and lithologically distinct belts within Prince William Sound identified by Plafker and Winkler (1994) as disconcordant mafic volcanic rocks and further defined by Kveton (1988). These belts include the more inboard Whale Bay-Bainbridge mélange belt, Latouche belt, and Montague belt (Fig.15).

Whale Bay-Bainbridge Belt

Of the three fault-bounded belts, the Paleocene to early Eocene Whale Bay and Bainbridge belts outcrops the furthest inboard in the Prince William terrane (Fig.14). The Whale Bay belt is predominately comprised of deep marine facies, comparable to flysch sequences, that include thick to medium bedded sandstones and finer, thinly bedded sandstones and mudstones that contain veins of low grade metamorphic minerals (Kveton, 1989). The Whale Bay belt is in fault contact with the Valdez Group and extends eastward where the west-dipping Bainbridge fault thrusts cohesive sedimentary rock of the Whale Bay belt on top of complexly deformed rocks of the Bainbridge mélange belt. These rocks include metamorphosed and folded sandstones and mudstones that have been intruded by mafic sills and pillow basalts (Kveton, 1988). Kveton defined the Whale Bay belt based upon its distinct structural characteristics that include a significant northwest dip, thrust faults, and series of open southeast trending folds (1988). The Bainbridge fault continues through the Knight Island ophiolite where it is interpreted that the Whale Bay rocks are in fault contact with the Knight Island ophiolite and the Bainbridge mélange belt occurs towards the top of the ophiolite. Further field observations provide evidence of this relationship where pillow basalts are interbedded with graded sedimentary flysch sequences (Tysdal et al., 1977).

Zircon fission track ages of 40-50 grains were obtained from three sandstone samples within the Whale Bay belt (Kveton, 1988) and yielded the oldest ages of the three belts. The furthest inboard and most westward sample yielded a young age population peak around 48 Ma and an older age population peak between 60 and 65 Ma. The next two samples were collected further east and indicated a general younging in grain ages. The young peak in the second sample occurs around 43 Ma and the older age peak occurs around 58 Ma. The third sample had the youngest grain population of the samples at 42 Ma and an older peak occurring around 52 Ma (Kveton, 1988). Results from samples taken within the Bainbridge mélange belt are omitted due to revised structural observations in which three of the samples thought to be part of the Bainbridge were from a faulted section of the Latouche Belt (Kveton, 1989).

Since Kveton, a more detailed thermal history for the Whale Bay-Bainbridge belt has been developed from U/Pb and fission track detrital zircon ages at three localities within the belts (Hilbert-Wolf, 2012). Three hundred grains were analyzed and averaging of the ten youngest grains yielded maximum depositional ages between 57 and 60 Ma. The belt's age of emplacement is constrained by two intrusive events including the 54 Ma Sanak Baranof plutons (Bradley et al., 2003) and the Eshamy suit pluton around 38 Ma (Johnson, 2012) supported by fission track ages that indicate partial resetting (Carlson, 2012). Currently, no U/Pb ages have been obtained from the inundated Knight Island ophiolite. However, the interbedded sediment within the pillow basalts of the ophiolite strongly correlate with the flysch sequences exposed in the Whale Bay belt. The U/Pb age from the Whale Bay belt can thus be applied to approximate the maximum depositional age of the Knight Island ophiolite to be 57 Ma.

Latouche and Montague Belts

The Middle Eocene Latouche and Montague Belts are separated from the Bainbridge mélange belt to the north by the Latouche Passage fault and are separated from each other by the Montague Strait fault based upon variations in metamorphic grades (Fig.14; Tysdal et al., 1979). The Latouche belt consists of sandstones with interbedded siltstones and mudstones in addition to thick conglomerate beds. The presence of conglomerates distinguishes the Latouche belt from the more inboard Orca flysch and indicates a more turbid, mid-fan depositional environment (Kveton, 1989). Several diagnostic features suggest that these two belts represent a time of later accretion. Petrographic results reveal that these rocks contain large volumes of sedimentary lithic clasts as opposed to the volcanic lithic clasts found in the more inboard flysch sequences of the central Valdez and western Orca Groups (Dumoulin, 1977). The sandstone compositions from the Montague and Latouche belts deviate from the magmatic arc provenance interpreted for the Valdez and western Orca sandstones. Instead, these regions indicate a more mature, recycled source such as sediment coming from the subduction complex (Dumoulin, 1977). Another pivotal difference between the western and eastern Orca belts relates to the timing and emplacement of forearc magmatism. Unlike the Whale Bay and Bainbridge belts, the Latouche and Montague belts do not contain the volcanic rocks, ophiolites, and plutonic intrusions found further inboard. Since these features are associated with the subduction of a ridge in a trench-ridge-trench setting, it can be interpolated that these belts accreted after the mid-Paleocene to early Eocene event. Their age is somewhat constrained from diagnosis of middle to late

Eocene microfossil assemblages though ambiguities arise in providing a lower age limit. Whereas the inboard ages were constrained by the plutons, the outboard ages are devoid and, as such, their timing of emplacement unresolved.

The same thermochronometric (Kveton, 1989; Carlson, 2012) and geochronologic (Hilbert-Wolf, 2012) studies conducted in the Whale Bay and Bainbridge mélange belts were implemented in the Latouche and Montague belts. Zircon fission track ages were obtained from two sandstone samples within the Latouche belt. Both samples yielded the youngest age populations of the three belts and diminutive populations of older ages. The first sample produced a young age population peak of 36 Ma with a slight older age population peak around 57 Ma. The second sample's young age population peak occurs around 35 Ma with no obvious older age peak (Kveton, 1988). The validity of age results from these samples is contingent upon further assessment of the thermal events and possible resetting of fission tracks.

U/Pb detrital zircon and additional zircon fission track ages were obtained from five localities within the Latouche and Montague belts (Hilbert-Wolf, 2012; Carlson, 2012). U/Pb analyses on two hundred grains from the Latouche belt yielded early Eocene age peaks. Both samples contained young grains of 38±0.6 Ma and 41± 1.6 Ma with maximum depositional ages between 38-40 Ma. Shortly after its accretion, the Latouche belt was intruded by the 38 Ma Eshamy suite plutons (Johnson 2012) indicated by low-grade greenschist facies and partial resetting of zircon fission tracks (Carlson, 2012). In the Montague belt, U/Pb ages from three different localities yielded the youngest depositional age populations between 34-35 Ma (Hilbert-Wolf, 2012). Based upon the 38 Ma intrusion of the Eshamy suite pluton (Johnson, 2012), Upper Eocene age outboard parts of the Montague belt likely accreted after the intrusion which coincides with the absence of metamorphism affirmed with preserved zircon fission track cooling ages (Carlson, 2012).

Resurrection Peninsula Ophiolite

The Resurrection Peninsula ophiolite expands over 21 km of land (Plafker et al., 1994) and comprises the Resurrection Peninsula within the Resurrection Bay off the coast of Seward, Alaska (Fig.3). The partial ophiolite sequence begins on the eastern side with ultramafic rock, gabbro, sheeted dikes, and is topped on the western side by thick bedded pillow basalts (Fig.7). The sequence has experienced low grade metamorphism with observed greenschist facies minerals from chlorite to biotite and intercalated pods of serpentinized ultramafic pyroxenite and peridotite attributed to hydrothermal metamorphism that occur in gabbros as well as in the footwall block contact with thrusted flysch (Plafker et al., 1994; Kusky et al., 2004; Bradley et al., 2006). The gabbros within the sequence have been divided into western and eastern based upon stratigraphic relationships and possible structural displacement (Bradley et al., 2006). The gabbros on the western side occur as massive medium to coarse grained beds with distinct mineralogical layering of alternating amounts of plagioclase and pyroxene. On the eastern side, gabbros are intruded by large plagiogranite dikes that increase up sequence and contain small prehnite veins and larger volumes of intercalated ultramafic pods (Miller, 1984). Based upon these differences, Miller (1984) concluded the eastern gabbro most likely formed lower in the ophiolite sequence and has since been displaced. The largest of these plagiogranite dikes, measuring 20 meters wide, occurs on Killer Bay and intrudes the gabbro complex and sheeted dikes (Kusky et al., 2004). It is at this location where the U/Pb zircon age of 57±1 Ma that defines the age of the ophiolite was obtained (Nelson et al., 1989). Towards the center of the peninsula, the gabbros grade into sheeted northwest to northeast trending basaltic dikes of aphanitic to diabasic textures as observed for this study on the western side of the sequence in Humpy Cove (Kusky et al., 2004;Bradley et al., 2006). The western side of the ophiolite is mostly composed of well-preserved pillow basalts with average diameters of 0.5 m (Bradley et al., 2006) and estimated thickness of 1000 m (Kusky et al., 2004; Tysdal et al., 1977; Nelson et al., 1987). The pillows contain interbedded flysch and turbidic sediments in addition to red and green chert (Kusky 2004; Nelson and Nelson, 1993). Certain areas indicate slight alteration from low-grade metamorphism indicated by veins of chlorite, zeolite, and at times prehnite (Kusky et al., 2004).

On the same western side of the ophiolite, near Humpy Cove, the sedimentary rocks interbedded in the ophiolite are heated and hornfelsed. At this location, controversy surrounds the age and stratigraphic relationship of the ophiolite with adjacent clastic strata (see Bradley and Miller, 2006). Original mapping of the Resurrection ophiolite associated it with the Cretaceous Valdez Group, and hence it was thought to be Cretaceous in age (Tysdal and Case, 1979). Later mapping found the ophiolite follows along strike with the Paleocene-Eocene Ghost Rocks Formation in Prince William Sound and yields similar paleomagnetic results (Plumley, 1984; Bol et al., 1992). Based upon these similarities, the two were grouped together (Plafker, 1987) until a later age for the ophiolite was believed to mandate dissociation (Nelson et al., 1989). A U/Pb zircon date from an intrusive plagiogranite from Killer Bay on the east side of the Resurrection Peninsula constrains the age of the ophiolite at 57 ± 1 Ma; the Knight Island ophiolite (in Prince William Sound) is inundated but assumed to be the same age (Nelson et al., 1989). On the northeastern side of Resurrection Peninsula, a thrust fault is mapped between the ophiolite and Upper Cretaceous Valdez Group. On the western side of the Resurrection Peninsula ophiolite, two hypotheses contend with the stratigraphic affinity of surrounding clastic strata (Fig.7; cf. Bradley and Miller, 2006; Kusky and Young, 1999). The core of the controversy is whether the strata are Cretaceous Valdez Group and fault bounded or whether they are Paleocene and essentially in stratigraphic continuity with the ophiolite. Kusky and et al. (2004) argue for a depositional contact between the Resurrection ophiolite and overlying sedimentary sequence. To justify this relationship, they classify the sequence as part of the Orca Group based upon lithology distinct from the flysch of the Valdez Group and from its conformable nature with the ophiolite. Since the sequence is in stratigraphic continuity with the 57 Ma age of the ophiolite, interbedded with pillow basalts, and is intruded by 53.4 Ma plutons of the Hive Island stock (Bradley et al., 1999), it must be part of the Paleocene Orca Group (Kusky et al., 2004). Under this interpretation, the ophiolite was formed, buried and overlain by turbidic sediment, thrusted into its present location, and intruded by plutons within 3.6 ± 1.4 Ma years. The controversy of the relationship and related events of the ophiolite can thus be settled by determining the age of the sedimentary strata surrounding the Resurrection ophiolite.

Knight Island Ophiolite

The Knight Island ophiolite outcrops roughly 85 km northeast of the Resurrection Peninsula (Kusky et al., 2004) in the Prince William Sound terrane (Fig.12) but is believed to be continuous at depth with the Resurrection ophiolite based upon gravity and magnetic data conducted across Prince William Sound (Saltus et al., 1999; Case et al., 1966). Petrography and geochemistry of sub aerial exposures support provide further support for affinities between the Resurrection and Knight Island ophiolites. The lithology of the Knight Island ophiolite strongly correlates to the Resurrection ophiolite with gabbros, sheeted dikes, and pillow basalts of slightly greater (5000 m) thickness than that of those of Resurrection (Fig.14). Like Resurrection, the Knight Island ophiolite has experienced slight alteration from hydrothermal metamorphism evidenced by low grade zeolite to prehnite-pumpellyite facies as well as gabbro intrusions into surrounding sedimentary rock and mafic dikes (Kusky et al., 2004). The only notable difference is the Knight Island ophiolite does not contain intercalated pods of ultramafic rock. Rather, they are only observed on the beach shore as cobble to boulder sized rocks.

Evidence for Trench-Ridge-Trench Triple Junction

Unique volcanic activity outcrops along the western margin of North America from the Cascades and Coast mountain ranges in Oregon and Washington up to the Chugach-Prince William terrane in south-central Alaska. The activity is believed to have taken place from the Late Cretaceous to Late Eocene time, or between 70 to 35 Ma (Haeussler et al., 2003). During this interval, forearc magmatism and MORB ophiolite sequences with interbedded clastic sediment were generated at what is generally accepted to be the causal tectonic setting: the subduction of a mid ocean ridge at a trench-ridge-trench triple junction (TRT) along the western North American margin (Hudson, 1983; Sisson et al., 2003; Bradley et al., 2003; Kusky et al., 2004). The triple junction (Fig.10) implies the meeting of three plate boundaries at a point that creates particular plate margin geometries. In the case of a TRT triple junction, upwelling mantle asthenosphere causes the rifting of oceanic plates that creates a spreading center or ridge. As the spreading progresses and the ridge continues to form, the rifting oceanic plates are passively moved laterally in relation to the spreading motion and in the direction of the slab pull force exerted by an attached subducting oceanic slab. Eventually, the slab approaches the trench and undergoes the process of ridge subduction beneath a third overlying plate. Contemporaneously, oceanic crust being generated at the spreading center is in close proximity to the trench margin. The low density of young (<10 Ma) oceanic crust causes it to be more buoyant than the underlying asthenosphere (Cloos, 1993). Thus, the oceanic crust refuses to subduct and instead continues through the trench margin where it is buried by clastic turbidites before finally accreting to the overlying plate. With continued ridge subduction, a slab window is generated beneath the overriding plate. A slab window consists of a slab free region that occurs at a spreading center when the continuous upwelling of hot mantle asthenosphere consumes the cooler mantle lithosphere (Haeussler et al., 2003). Over time, spreading evolves and the slab window grows beneath the overlying plate. The interaction of the slab window with the overlying plate is recorded by forearc magmatism. Signature features of trench-subduction include basalt exposures with interbedded clastic rocks and a predominately MORB geochemistry with minor traces of incompatible elements as well as a series of near-trench plutons that intrude the forearc (Fig.10). As previously mentioned these assemblages expand the entire upper western margin and, as such, can be correlated.

Geochemistry and Paleomagnetism of Chugach-Prince William Ophiolites

As mentioned, the Resurrection and Knight Island ophiolites share distinguishing characteristics (Fig.7 and Fig.14): pillow basalts interbedded with clastic flysch sediments, sheeted dikes with one-sided chilled margins (Bradley et al., 2003), and magmas with MORB geochemical signature (Nelson and Nelson, 1993; Lytwyn et al., 1997; Kusky and Young, 1999). In a recent study, geochemical analysis was obtained from sheeted dikes and pillow basalts of both the Resurrection and Knight Island ophiolites (Lytwyn et al., 2000). The analysis confirmed that both ophiolites have predominately mid-ocean ridge basaltic signatures. The primary MORB signature from both ophiolites supports formation at a trench-ridge-trench setting in which the ophiolite was formed at a spreading center and shortly after accreted to the continental margin. However, as previous studies have also shown, there is a slight calc-alkaline overprint that occurs in the ophiolites' basalts. This secondary signature has been attributed to the ophiolite's formation near the continental margin (Lytwyn et al., 2000; Nelson and Nelson, 1993). The close proximity allowed turbidic and flysch-like sediments from the nearby accretionary wedge to be incorporated into the melt immediately following the ophiolite's inception. The same calc-alkaline overprint has appeared in volcanic rocks and intrusions within the Prince-William terrane including the adjacent and once correlated Ghost Rocks formation in Kodiak Island (Lytwyn et al., 2000). The distinct presence of andesites in the Ghost Rocks Formation with the MORB basalts suggests the assimilation of the sedimentary rocks from the forearc that introduced felsic signatures into the previously generated mafic melt. The previously mentioned paleomagnetic results from Resurrection Peninsula ophiolite and adjacent Ghost Rocks formation near the Knight Island ophiolite both indicate large northward translation relative to cratonic North America. The age of the Ghost Rocks formation is slightly older (~65 Ma) than the Resurrection Peninsula (~57 Ma). The time between them is accounted for in the slight difference between their displacement distances i.e. the older Ghost Rocks are believed to have been translated around 1500 km while the younger Resurrection ophiolite has estimated displacements around 1440 km (Bol et al., 1992).

Sanak-Baranof Pluton Belt

The Sanak Baranof belt (SBB) occur as plutonic intrusions whose limits coincide with those of the CPW accretionary complex beginning furthest west in Sanak Island around 61 Ma and continuing 2200 km east into Baranof Island around 51 Ma (Fig.2; Bradley et al., 2003; Kusky et al., 2004). Their presence in the forearc, migrational pattern, and timing coincide with ophiolite formation, near-trench metamorphism, gold-mineralization, and ductile and brittle deformation all present in the accretionary complex that support the subduction and subsequent migration of a slab window (Bradley et al., 2003). The proposed ridge subduction as the causal mechanism for the plutonic belt has gained wide acceptance since its initial suggestion (Marshak and Karig, 1977) as described by Bradley et al. (2003) based upon age, large expanse, and geochemical signatures (Fig.10). The granodiorite plutons are largely proliferated in the flysch of the Upper Cretaceous Valdez and Paleocene-Eocene Orca Groups. The presence of the pluton belt in the Upper Cretaceous flysch of the Chugach terrane including Shumagin Formation, Valdez Group, Sitka Greywacke and more inboard of the Prince William terrane including the Kodiak Formation, Orca Group e.g. Resurrection Peninsula/ Knight

Island, and Ghost Rocks Formation coincide with high temperature, low pressure metamorphism and alterations to flysch of the CPW (Hudson and Plafker, 1982; Sisson et al., 1989; Dusel-Bacon et al., 1993, 1996a,b; Weinberger and Sisson, 2003; Zumsteg et al., 2003) present in partial resetting of track ages (Carlson, 2012). In addition to Paleocene to Eocene plutons of the Sanak-Baranof belt, late Eocene to early Miocene Eshamy Suite plutons also intrude the western, further inboard Prince William terrane but their relation to the Sanak-Baranof belt and tectonic setting are not well understood (Johnson, 2012). The farther outboard Orca including the Latouche and Montague Islands were not intruded by plutons as further supported by an absence of resetting from fission track analysis (Carlson, 2012) and U/Pb maximum depositional ages (Hilbert-Wolf, 2012) that both suggests later accretion.

Though the locations, ages, geochemistries, and geologic relationships of the Sanak-Baranof plutons, ophiolites, and other products of the T-R-T triple junction have been well-accepted, the location of the subducting ridge and inclusive CPW terrane has been highly controversial between two main competing models with varying plates and their associated geometries (Fig.11; cf. Haeussler et al., 2003 vs. Cowan, 2003). These contesting hypotheses propose varying plate geometry models for the trench-ridge-trench boundary that invoke two different locations of the CPW terrane prior to 50 Ma. The first argument corroborates previously mentioned paleomagnetic data from the Ghost Rocks Formation and Resurrection Peninsula (Plumley et. al., 1983; Bol et. al., 1992) to support that prior to its intrusion, the CPW terrane laid 1100 kilometers south of its present location. Around 50 Ma, northward migration of29 the terrane occurred over the slab window and resulted in a southward migration of the Sanak-Baranof pluton belt (Cowan, 2003). The second argument favors a more in-situ location for the CPW terrane. The observed widespread plutonism from southern Alaska to the coasts of Washington and Oregon was not generated from a single trench-ridge-trench encounter and slab window location. Rather, it was caused from two slab window locations: a T-R-T junction at the CPW in southern Alaska and a second T-R-T boundary along the Washington and Oregon coastal ranges. For this to be possible, an additional “Resurrection” plate (Fig.11) is incorporated to generate two locations of ridge subduction occurring at two different trench-ridge-trench triple junction boundaries (Haeussler et al., 2003). Based on this hypothesis, the Resurrection Peninsula ophiolite was formed at the spreading ridge adjacent to the present margin of the Chugach-Prince William terrane thus discounting the paleomagnetic results that invoke large northward translation. Haeussler et al., (2003) discounts the paleomagnetic data for the Resurrection Peninsula ophiolite (Bol et al., 1992) and for the Ghost Rocks Formation (Plumley et al., 1983). He believes the data is invalid based on inaccuracies he associates with the implementation of a two-fold test to correct for structural tilt. Haeussler also points out that the ophiolite was accreted sometime after its formation into the preexisting accretionary complex. Therefore, since it is not a part of the CPW terrane its paleomagnetic data cannot be applied (Haeussler et al., 2003).

Methods

U/Pb Geochronology

U/Pb ages were collected along a transect A-A’ (Fig. 3) that spans the width of the Chugach terrane (Fig.17). The two furthest inboard samples collected for U/Pb zircon analysis were obtained from one sample along the Sterling Highway between Anchorage and Homer (RB12-11) and a second sample farther along the Sterling Highway between Cooper's Landing and Quartz Creek (RB12-12). In order to complete the transect and to address the age of the clastic rocks and thus the ophiolite's western contact, four sandstone samples were collected in the Resurrection Bay area (Fig. 8; RB12-01, 02, 04,08) along Nash Road (across the end of the bay from Seward), within Humpy Cove, and two at the edge of Thumb Cove. Sample RB12-04 (Fig.16) represents a critical contact relationship where a thin-bedded, medium-grained sandstone is interbedded with (and crosscut by) basaltic rocks, thus providing a key tie to the ophiolite. Raman spectroscopy was conducted on samples from the Valdez Group and two Orca populations (older aged sample from ophiolite and younger aged samples from Montague Island) to evaluate Uranium damage trends and diagnose a potential provenance for the Chugach-Prince William terrane (see below).

The U/Pb detrital zircon data were measured to constrain the timing of maximum deposition and illuminate the provenance of material across the Chugach terrane, with a specific focus on the Resurrection Bay area samples near Seward, Alaska. The U/Pb geochronology is a well-established technique (Gehrels et al., 2008) that employs multiple calibration standards. The difference between the standards' U/Pb ages and their known ages helps account for levels of precision and accuracy in conducting U/Pb detrital zircon analyses (Gehrels, 2010).

Before performing the analyses, the zircons must first be isolated from the rest of the sample. Isolation of zircon minerals involved initial pulverization, grain size filtering, and heavy liquids density separation. For each sample, one hundred grains were randomly selected to capture prominent grain age populations as well as encapsulate general trends. The detrital signals also assist in diagnosing a provenance for sedimentary rocks and to determine a maximum depositional age based on the youngest zircon ages in the sample. The U/Pb ages were obtained using the LA-MC-ICPMS at the Arizona LaserChron Center (Gehrels et. al., 2008). The LA-MC-ICPMS is a notable technique based upon its precision and effectiveness that allow large volumes of data to be extracted from a variety of grain sizes (Gehrels et al., 2010). Standards were used for calibration after every ten grain analyses.

Raman Spectroscopy

To understand provenance of the clastic cover to the Resurrection Bay ophiolite, Raman Spectroscopy was applied to Precambrian zircons from samples obtained across the Chugach-Prince William terranes. Going in the outboard direction, grains were analyzed from the Upper Cretaceous Valdez Group, Resurrection Bay (old Orca), and the Montague and Latouche Islands (young Orca). The Raman method applies a laser of standard wavelength to grains with known U/Pb ages. A CCD collector records the positive shift in wavelength (Raman wavenumber shift) that results from the laser light interaction with bonds of the silica tetrahedra. The Raman wave number (Fig.24) was obtained for three main peaks. The peaks' positions, intensities, and widths are a function of the radiation damage inherent in the crystal (Marsellos and Garver, 2009). This relationship is shown over time such that as the effective uranium content (eU in ppm) decreases from continuous damage, the Raman wave number increases. As a result, the damaged or partially annealed grains exhibit a descending oblique trend when effective uranium content is plotted against Raman wavenumber. However, if the grain contains no uranium damage, the Raman wavenumber remains at a constant high value (1007.5 to 1008.0 for v3(SiO_4) indicating that full annealing has occurred around temperatures of crystallization.

Raman measurements were made with a Bruker Optics Senterra® Spectrometer coupled to an Olympus® BX51 reflected light microscope at Union College. Raman spectroscopy was performed using a 633 nm external He-Ne laser. The spectrometer includes a computer controlled three-grating turret with a spectral resolution up to 3 cm^{-1} and automatic laser and Raman frequency calibration. Samples were first located at 100x using bright field objectives, and the measurements were made with video camera and long working-distance dark field objectives at 500x. The signal was captured by a low noise 1024x256 pixel thermoelectric-cooled CCD detector. Measurements were made with a laser power of 20 mW, and an aperture of 25 x 1000 mm. An integration time of 15 to 25 s was used during acquisition of the Raman shift, and automated collection was done for background and monochromatic wavelength. For samples with a very strong peak to background ratio, we used a simple rubber band background correction, but for those with a more elevated background or a background broadly concave (likely due to slight fluorescence), we used a concave rubber band background correction. We then used FitYK® for peak fitting and we concentrated our efforts on the V_1SiO_4 (~974 cm^{-1}) symmetric stretching and the V_3SiO_4 (~1007 cm^{-1}) antisymmetric stretching (i.e. Marsellos and Garver, 2010). We use a Gaussian/Lortenzian approximation using the Levenburge-Marquardt method. Each grain was measured twice in slightly different spot locations that tended to vary by less than 20 um, and grains were oriented with c-axis in a N-S position. The reported values for the Raman modes are the average of the two spot measurements. The average variation in measurements for the V_3SiO_4 mode was 0.21 cm^{-1}. Error on the Raman wavenumber is shown as the Standard deviation of the two measurements, and for eU it is estimated at 20%.

Results

U-Pb Geochronology

We successfully dated around 100 grains in each of the six samples collected along the Chugach terrane transect: RB12-01, RB12-02, RB12-04, RB12-08, RB12-10, and RB12-12 (Fig. 17). From the amount of grains analyzed in each sample, a representative U/Pb detrital signal was obtained and the ten youngest grains were averaged to yield maximum depositional ages. RB12-10 was collected the farthest inboard of the Chugach terrane and begins the study transect adjacent to the border between the late Jurassic to Cretaceous McHugh Complex and the Upper Cretaceous Valdez Group. U/Pb ages were obtained from ninety-five grains yielding a detrital signal and a maximum depositional age of 156.5 Ma. Both of these results coincide with previous U/Pb analyses of the McHugh Complex (Amato and Pavlis, 2010) thus classifying the sample as part of the McHugh Complex. The ages also correlate with the currently mapped boundary between the McHugh Complex and the Valdez Group. Based upon the sample's age, discontinuous mélange assemblage, and position in the accretionary complex, sample RB12-10 records the early stages of subduction and formation of the Chugach accretionary wedge. Sample RB12-12 was taken along the middle of the transect that corresponds to the interior of the Chugach terrane and central Upper Cretaceous Valdez Group. U/Pb analysis was conducted on 107 grains that yielded a detrital signal and maximum depositional age of 70.9 Ma consistent with the Upper Cretaceous Valdez Group. Like the McHugh Complex, these results reinforce previous U/Pb analyses of the Valdez Group (Kochelek et al., 2011) as well as the present geologic mapping of the interior Chugach terrane.

Four samples (RB12-01, RB12-02, RB12-04, RB12-08) were collected in the Resurrection Bay area off the coast of Seward, Alaska. In this area, a previous U/Pb zircon date from an intrusive plagiogranite from Killer Bay on the east side of the Resurrection Peninsula constrains the age of the ophiolite at 57 ± 1 Ma (Nelson et al., 1989). However, the age has been questioned based upon the size of the dataset as well as the possibility that the plagiongranite intrusion could represent a later time of spreading after the ophiolite’s formation (Kusky et al., 2004).

Sample RB12-08 was taken from along Nash Road (across the end of the bay from Seward) above the Resurrection Peninsula. Ninety-eight grains taken from this sample yielded a maximum depositional age of 60.1 Ma. Samples RB12-01 and RB12-02 were collected along the outer area of Thumb’s Cove in Resurrection Bay along the western side of the Resurrection Peninsula. Ninety-four grains from RB12-01 yielded a maximum depositional age of 61.1 Ma. 101 grains from RB12-02 yielded a similar maximum depositional age of 60.7 Ma.

Sample RB12-04 was obtained from the top of the ophiolite sequence on the western side of Resurrection Peninsula where clastic sediment is interbedded within the pillow basalts of the ophiolite sequence. The field relationship of these sediments implies that they were deposited within the ophiolite sequence before the ophiolite had cooled thus allowing them to become incorporated within the recently formed pillow basalts. These sediments were thus deposited almost immediately after the formation of the ophiolite in which their age will provide a key tie to the age of the ophiolite that up to this point has been doubted. U/Pb ages from 111 grains in RB12-04 yielded a young maximum depositional age of 57 Ma given by a robust mode formed from the youngest four zircons. Remarkably, this is identical to the age from a plagiogranite (Nelson et al., 1989) located on the eastern side of the ophiolite sequence, reinforcing the 57 Ma age of the ophiolite.

The Contact Fault currently serves as the boundary where rocks to west of it are the Upper Cretaceous Valdez Group of the Chugach terrane and the rocks to the east are part of the Paleocene to Eocene Orca Group of the Prince William terrane. If the sample is part of the Valdez Group, its detrital signal would contain two dominant grain age populations: a prominent peak in the Late Cretaceous and a more subtle peak in the Late Jurassic. If the sample is part of the Orca Group, its detrital signal would contain two different main grain age populations: a prominent Paleocene to Eocene peak and a more subtle but still significant Late Cretaceous peak. Samples RB12-01, RB12-02, and RB12-08 were taken from sediment surrounding and above the Resurrection Peninsula that is currently mapped as part of the Upper Cretaceous Valdez Group. However, all three samples contain maximum depositional ages between 60-61 Ma (Fig.18 and 19) and their detrital signals show two main age populations in the Paleocene to Eocene and Late Cretaceous that coincide with the Orca Group of the Prince William terrane. In addition, the Resurrection Peninsula’s grain age populations show a clear correlation (Fig.19) when compared with previous U/Pb zircon detrital signals of the Orca Group 70-80 km to the NE in Prince William Sound (Hilbert-Wolf, 2012). These units lie to the right of the Contact Fault and, as such, are part of the Prince William terrane. In order to account for the Orca Group in the Resurrection Peninsula, the location of the Contact Fault must then be revised and the Prince William terrane expanded westward.

Raman Spectroscopy

Comparing the trends produced by radiation damage with grains of known U/Pb age can provide insight into past thermal events of a given area. Raman spectroscopy was conducted on detrital Precambrian grains from the ~72 Ma Valdez Group, ~57 Ma older Orca Group (Resurrection Peninsula Ophiolite), and ~35 Ma younger Orca Group (PWS Montague Island – from Hilbert-Wolf, 2012) (Fig.25). The Precambrian grains of the ~72 Ma Valdez Group exhibit a trend suggesting significant radiation damage accumulation with no crystalline grains. The Raman wavenumber of the Precambrian grains of the ~57 Ma older Orca Group have a similar trend of radiation damage, but a single Precambrian grain is nearly crystalline, which represents 20% of the total grain population. The Precambrian grains of the ~35 Ma Orca Group essentially falls into two distinct populations: one with a damaged trend similar to the first two groups; and the other with a significant (45%) fraction of grains that are crystalline or nearly so. The grains then exhibit a boomerang pattern in which they spread across a partially annealed zone of damage into an annealed zone of zero damage. The overall Raman signal along the CPW terrane indicates that moving outboard into younger units coincides with a gradual increase in the annealing of Precambrian grains.

Discussion

U-Pb Geochronology

Samples RB12-10 of the Late Jurassic to Cretaceous McHugh complex and RB12-12 of the Late Cretaceous Valdez Group proved consistent with the previously obtained U/Pb detrital zircon ages, current mapping of the Chugach terrane, and the Eagle River thrust fault that serves as the boundary between the two groups (Fig.18). The ages of the samples invoked constraints on the study transect across the Chugach terrane in addition to providing U/Pb detrital signals. These unique signatures were used in a comparison analysis to help in determining the U/Pb detrital signal from the Resurrection Bay area specifically whether it has a Valdez or Orca signal (Fig.19). The U/Pb zircon ages of the samples taken from within Resurrection Bay are an indispensable piece in determining the relationship of the Resurrection Peninsula ophiolite to the CPW terrane. The cumulative U/Pb detrital zircon signature of the Resurrection Bay area was compared to the cumulative grain age populations of the 492 grains dated from the Valdez Group (RB12-10; Kochelek et al., 2011) and the 2,786 grains dated from the Orca Group (Hilbert-Wolf, 2012).

Kuiper Statistical Analysis

In order to further analyze and define the anomalous U/Pb detrital zircon ages from the Resurrection Bay area, cumulative frequency plots of the data were generated (Fig.19 and 20) using the two-sample Kuiper non-parametric statistical test, a modified version of the Kolmogorov-Smirnov technique (Press et al.,1992). Often with the probability density plots traditionally used to display U/Pb data significant relationships between the datasets can get overlooked. The Kuiper statistical analysis addresses this issue with the two-sample Kuiper test that implements a non-parametric statistical method comparing two cumulative distributions of data or, in this case, U/Pb detrital zircon age populations. The Kuiper statistic finds the maximum differences both in the upper and lower ends of the two population distributions on the cumulative distribution plots of the data being compared. A p-value can then be calculated based on the amount of calculated difference value and for the number of observations within the datasets. The p-value defines the null hypothesis that, if satisfied, proves the data populations are not different for a specified confidence interval. As the difference between populations decreases, the p-value increases such that the populations that are least different from one another will have higher p-values. These populations are more prone to satisfy the null hypothesis and thus cannot statistically be proven different.

Kuiper Statistical Analysis: Comparing Resurrection Bay to Valdez and Orca Groups

In the first cumulative frequency plot (Fig.20), the Kuiper test was done on three different U/Pb grain age population distributions of cumulative data obtained from the Upper Cretaceous Valdez Group (RB12-10; Kochelek et al., 2011), the Paleocene to Eocene Orca Group (Hilbert-Wolf, 2012), and the Resurrection Bay area (RB12-01,RB12-02,RB12-04, RB12-08). The reported p-value for the Resurrection Bay area and the Valdez Group is 0.00, indicating the grain age distributions for the Resurrection Bay area are different from the Upper Cretaceous Valdez Group with a 95% confidence interval. The p-value for the Resurrection Bay area and the Orca Group in Prince William Sound (PWS) is 0.8112 which indicates the Resurrection Bay area is not different from the Orca in PWS with a 95% confidence interval. The resulting statistical analysis thus confirms the previous observational comparisons of the dominant grain age populations that the Resurrection Bay area is in fact part of the Paleocene to Eocene Orca Group.

Because the samples of Resurrection Bay were from clastic sediment that occurred adjacent to, above, and interbedded with the ophiolite, their classification as the Paleocene to Eocene Orca Group addresses the two main issues of the study: the age of the ophiolite and its structural emplacement into the accretionary complex. The 57 Ma robust age peak from the sediment interbedded with the ophiolite at the top of the sequence confirms the age of the ophiolite and is continuous with the U/Pb ages obtained from the bottom (intruded gabbro) of the ophiolite sequence. The samples taken from sedimentary strata around the ophiolite, including above the ophiolite (RB12-08) and the top of the ophiolite (RB12-01, RB12-02) define the ophiolite’s relationship to the accretionary complex. In the present geologic map (Fig.?), the western side of the Resurrection Peninsula ophiolite is simply in fault-bounded contact with Upper Cretaceous strata of the Valdez Group. The U/Pb ages of detrital zircon from four samples from the Resurrection Bay area show these strata can be correlated to the Paleocene-Eocene aged Orca Group of the Prince William terrane (Fig. 3b). Not only does this contradict present terrane boundaries but it settles the controversy surrounding the western contact of the Resurrection Peninsula ophiolite (cf. Bradley and Miller, 2006; Kusky and Young, 2004). The ages of these samples thus confirms the crux issue: 1) is the sediment part of the Upper Cretaceous Valdez Group in which the ophiolite is in thrust contact and thus unrelated to the accretionary complex or 2) is the sediment Paleocene to Eocene in age and part of the Orca Group in which the ophiolite is in depositional continuity and part of the accretionary complex. From comparison of the PDP plots of the U/Pb age populations and statistical analysis using the Kuiper test, the clastic sediment in question is in fact the Paleocene to Eocene Orca Group. Therefore, the ophiolite is in depositional continuity with the sedimentary strata and part of the accretionary complex.

Kuiper Statistical Test: Comparing Resurrection Bay to Fault-Bounded Orca Group Belts in Prince William Sound

The samples from clastic units interbedded with and above the Resurrection Peninsula ophiolite are Paleocene to Eocene and part of the Orca Group. A key question is how well they compare to previously dated units of the Orca (Hilbert-Wolf, 2012). The cumulative probability plot of the Resurrection Bay samples were compared to U/Pb age populations (Hilbert-Wolf 2012) from different tectonostratigraphic belts (Whale Bay Belt, Latouche Belt, and Montague Island) of the Orca Group within western Prince William Sound (Kveton, 1989) by generating additional cumulative frequency plots using the Kuiper statistical test (Fig.21).

The resulting p-value between the Resurrection Bay area and Latouche and Montague Islands is 0.00, indicating the U/Pb age population distributions are different (Fig. 5b) with 95% confidence. However, the p-value resulting between the Latouche and Montague age population distributions is 0.203, indicating that the null hypothesis that the two areas have a similar source cannot be rejected at the 95% confidence level. These results fit with the younging outboard trend in the accretionary wedge as the ages progress from the Resurrection Bay area and Whale Bay Belt to the farther outboard, younger Orca Group in the Latouche Belt and Montague Island. These findings coincide with evidence of the intrusion of the Sanak Baranof plutonic belt. The intrusions are present in the older Orca Group on the Resurrection Bay Peninsula and the farther inboard members of the Orca Group in PWS. The younger outboard Orca of the Latouche Belt and Montague Island have a different age signal than the more inboard Orca and are not intruded by the plutons that support previous hypothesis suggesting later accretion of the outboard areas (Plafker et al., 1997; Kveton, 1989).

The calculated p-value between the Resurrection Bay and Whale Bay Belt is 0.811 and, as such, the two populations are not different with a 95% confidence level. The striking similarity between the two data populations has further implications for correlating the Resurrection Peninsula with the Prince William Sound terrane. As previously mentioned, U/Pb detrital zircon ages have not been obtained from the Knight Island ophiolite in PWS. However, the Knight Island ophiolite is within the Whale Bay Belt and U/Pb ages have been obtained from adjacent localities. From these correlations, the U/Pb ages of the Whale Bay Belt can be applied to the Knight Island ophiolite. The same reasoning has been applied in order to tie U/Pb ages obtained from the Resurrection Peninsula ophiolite to the Knight Island ophiolite based upon similar geochemistries, metamorphic grades, compositions, and structures (Kusky et al., 1999, 2004; Dumoulin, 1977; Bradley et al., 2004). The quantitative U/Pb age population similarities demonstrated by the cumulative frequency plots (Fig.19 and 20) thus reinforces the previous qualitative similarities between the Resurrection Bay and Knight Island ophiolites. In addition, the ophiolite sequences have been correlated to the Orca Group Ghost Rocks Formation on Kodiak Island. The connection between these three members of the Orca Group links together previously reported paleomagnetic data that has important implications for the location of the T-R-T triple junction and tectonic evolution of the Chugach-Prince William terrane.

Raman Spectroscopy

For Precambrian zircon grains to be reset, and achieve a high degree of crystallinity, they must have reached high temperatures capable of driving full annealing in the crystal structure. Potential mechanisms for this heating include deep burial and subsequent exhumation or intrusion of a nearby pluton. Though plutons are recorded and prevalent throughout the Chugach terrane, the ~57 Ma Orca sample was adjacent to a mafic intrusion but did not experience significant resetting. In addition, intrusions would not account for a gradual trend of annealing across a broad transect of varying ages but rather would result in focused areas of reset grains. Therefore, the potential cause of increased annealing with younger depositional ages could correspond to erosion of the source terrain to increasing depths by exhumation over time. Because increasing depths coincide with increasing metamorphic grades, the potential source would be supplying sediment of increasing temperatures sufficient for annealing. Thus it is possible that the emergence and increase in the number of crystalline Precambrian grains up section may record unroofing in the source terrane (Fig.25).

Paleomagnetic Evidence for the Chugach-Prince William Terrane

Ghost Rocks Formation

Two separate paleomagnetic studies have been conducted on the Ghost Rocks Formation in the Kodiak Islands (Plumley et. al, 1983; O’Connell et al., 2007; Gallen, 2008), with a focus on Alitak Bay and 80 km west at Kiliuda Bay within the formation. The initial study was conducted by Plumley et al. (1982, 1983), who collected paleomagnetic data from pillow lavas at the two above localities. Of the two localities, 187 cores were taken from a tuff unit and 28 from basaltic and andesitic lava flow deposits. Based on results from fold tests, reverse polarity tests, and structural relations, the remanent magnetization was acquired during the initial cooling and crystallization of the lava flows. Structural corrections to the paleohorizontal yielded a 122^{o} variation in declination measurements of mean primary directions between lava flows of Kiliuda Bay and those of Alitak Bay but only a 12^{o} variation in mean inclination (Plumley et al., 1982, 1983). Despite these significant differences, the two areas are within the same formation and along strike. As such, Plumley believes they record the same inclination of remanent magnetization. The paleomagnetic results were then combined from the two areas in order to obtain a representative paleolatitude of the Ghost Rocks Formation 60-65 Ma years ago. The mean inclination found (40±6°) was much shallower than the expected paleolatitude of the current location (68±5°) and indicate a northward translation of 25±7° or ~3000 km since the Early Paleocene (60-65 Ma).

A paleomagnetic study conducted by Gallen (2008) in collaboration with O’Connell et al. (2007) , expanded on by Plumley (1982, 1983) by increasing the number of samples and broadening their localities and lithologies for paleomagnetic data. The study aimed to correct for the discrepancies between the two sample sites (Alitak Bay and Kiliuda) published by Plumley et al. (1983). Gallen incorporated 176 samples sites at four localities that included the same previous areas of Alitak and Kiliuda Bay as well as expanded the area to include Jap Bay. Three hundred cores in Jap Bay and 500 cores from Alitak Bay were collected with lithologies ranging from sedimentary rocks, conglomerates, volcanic flows, plutons, and volcanic breccia. Gallen reports paleolatitudes of 41°±8° that suggest the Ghost Rocks Formation experienced over 1500 km of translation from the Paleocene to the present (Fig. 21a)

Resurrection Peninsula Ophiolite

Two paleomagnetic studies have been conducted on the Resurrection Peninsula ophiolite. The initial paleomagnetic study done by Hillhouse and Gromme' (1977) on samples taken from sheeted dikes and pillow basalts indicated large poleward displacement of 24°±9. Subsequent U/Pb dating established a younger age of the ophiolite that required significantly less translation to take place to correspond with a shorter time interval. The study was expanded by Bol et. al (1992) by collecting multiple (4-8) cores from each sample site of dikes (Killer Bay, Cape Resurrection, Spud Lake, and Humpy Cove) and pillow basalts (Good Cove, Porcupine Glacier, Humpy Cove, Hat Cove, and Sandpit Cove). Bol applied structural corrections based on the vertical orientation of sheeted dikes and the horizontal orientation of pillow basalts to apply five methods of structural corrections to account for tilt. The paleomagnetic results of Resurrection Peninsula indicate a southern paleolatitude of a 13°±9° or approximately 1440 km of northward translation. Bol describes previous petrographic observations from the adjacent Kodiak Island in which exposed granitic intrusions and pillow basalts interbedded with clastic sediments are similar to those of the Resurrection Peninsula. Bol concludes the similarities allow the paleomagnetic results of Resurrection Peninsula apply to the entire Chugach-Prince William terrane. In addition, Bol notes that previous data including isotope compositions, correlating lithologies, ages, and petrographic studies support the Coast Mountains as a potential provenance for the Cretaceous to Eocene groups in the Chugach Mountains and the Coast Mountains Orogen as a potential provenance for the Kodiak Islands. The potential variance in provenance would be consistent with translation occurring during the timing of uplift and later exhumation along coastal margins.

Prior to this study, the paleomagnetic results from the Resurrection Peninsula ophiolite were discredited based on the ambiguities of the ophiolite's relationship to the accretionary wedge (Haeussler et al., 2003). To justify the existence of the in-situ slab window location generated by the Resurrection plate T-R-T triple junction, Haeussler et al., (2003) challenges the paleomagnetic data for the Resurrection Peninsula ophiolite (Bol et al., 1992) and for the Ghost Rocks Formation (Plumley et al., 1983). The authors argue the data are invalid based on inaccuracies associated with the implementation of a two-fold test to correct for structural tilt. Haeussler et al. (2003) also point out that the ophiolite was accreted sometime after its formation into the preexisting accretionary complex. Therefore, since it is not a part of the CPW terrane its paleomagnetic data cannot be applied (Haeussler et al., 2003).

The relationship established by the U/Pb detrital zircon results from this study call for a reevaluation of the paleomagnetic data of the Resurrection Peninsula ophiolite (Bol et al., 1992) that indicate >1400 km of northward displacement and its application to the entire Chugach-Prince William terrane. The Paleocene-Eocene ages of conformably overlying strata prove the ophiolite is in fact in depositional continuity and, as such, a part of the accretionary complex. These results dismiss previous speculations and validate the utilization of the translation results to the entire CPW terrane. Therefore, the paleomagnetic data obtained from the Resurrection Peninsula ophiolite and, concurrently, the Chugach-Prince William terrane indicate a paleolatitude 13 ± 9° south of the present location to near present day northern Washington (Bol et al., 1992). These results, in addition to those of the slightly older Ghost Rocks Formation (<1500km), support large coast parallel transport of the CPW terrane since the Paleocene and the search for provenance of the clastic rocks may include terrains now far to the south off the coast of present day Washington (Fig. 21b)

Insight into Possible Provenance

Paleomagnetics

The age of the Ghost Rocks formation is slightly older (~65 Ma) than the Resurrection Peninsula (~57 Ma). This slight age difference, however, makes a significant (~100 km) difference between their displacement distances. As such, the older Ghost Rocks are believed to have been translated around 1500 km while the younger Resurrection ophiolite has estimated displacements around 1440 km (Bol et al., 1992).If the paleomagnetic data from the Resurrection Peninsula and Ghost Rocks are honored, the Chugach-Prince William terrane would have been located farther south of its present day location near the present day Olympic Peninsula (Bol et al., 1992) between ~65-57 Ma. Several similarities exist between the Chugach terrane and those of the Crescent terrane (Fig. 22) in northern Washington including timing of events and resulting lithologies. The Olympic Mountains consists of the Olympic Core terrane of Eocene to Miocene metamorphosed turbidites (Tabor and Cady, 1978) and the Crescent terrane of early Tertiary basalts subsequently underthrusted by marine sedimentary rocks (Denny, 2012). The Crescent terrane extends along the coasts of Oregon and Washington up to the Mechosin Igneous Complex on southern Vancouver Island where the Leech River fault (Fig. 23a) serves as the northern boundary (Warnock et al., 1993). The Crescent terrane is comprised of mostly Paleocene to Eocene basaltic rocks with igneous complexes commonly classified as partial ophiolite sequences (Massey 1986; Clowes et al., 1987). The basalts have been categorized into two groups (Tabor and Cady, 1978): the Lower Crescent submarine unit with and the Upper Crescent sub aerial unit both with similar geochemistries and metamorphic grades ranging from low grade prehnite-pumphellyite to greenschist facies (Denny, 2012)

Geologically Similar Units

Underlying the Crescent terrane is the Blue Mountain unit that contains packages of submarine fan deposits including thick bedded, grey to black turbidic sandstones, argillites, siltstones and conglomerates that have experienced low-grade metamorphism to zeolite facies (Tabor and Cady, 1978). The clastic sediment of the Blue Mountain unit is overlain and interbedded with pillow basalts of the Lower Crescent formation (LCr). The LC coincides with volcanism from ~58-56 Ma while the overlying Upper Crescent formation (UCr) indicates sub aerial volcanics occurring from ~50-51 Ma (Duncan, 1982; Clark, 1989). These ages fall within the interpreted six million year interval (56-50 Ma) of northward migrating magmatism estimated by Pyle et al. (2009) from coccolith, U-Pb, and Argon-Argon dating.

The formation and tectonic setting of the Crescent basalts and igneous complex units has been controversial for almost fifty years. Interpretations cover a variety of plausible driving mechanisms (Denny, 2012) including a mantle plume (Simpson and Cox, 1977; Duncan, 1982; Wells, 1984; Pyle et al, 2009) forearc extension and consequent rifting (Wells et al., 1984, Babcock et al., 1992), or a migrating slab window (Breitsprecher et al., 2003; Haeussler et al., 2003; Masen et al., 2006). Though the tectonic mechanism for the Blue Mountain unit and overlying Crescent terrane remain unknown, they share apparent similarities with the Orca Group of the CPW terrane further north in south-central Alaska. If the paleomagnetic data from the CPW terrane is honored, the resulting paleolatitude places the terrane at a location adjacent to where these units currently outcrop. Like the Blue Mountain unit, the Orca Group consists of deep marine flysch sequences that contain thick monotonous packages of massive, coarse bedded turbidic sandstones with thin layers of siltstone and shale. Slightly older (~61 Ma, this paper) clastic sediments from the Orca Group conformably overlie and interbed ~ 57 Ma (this paper) pillow basalts just as deep marine sediments from the Blue Mountain unit overlie and interbed ~58-56 Ma pillow basalts of the Lower Crescent formation (Duncan, 1982). Both the Lower Crescent formation and the Orca Group were both formed during the Eocene and share distinct stratigraphic relationships. However, in order for the two groups to be proven as a once contiguous unit, further U/Pb detrital analysis must be conducted in addition to a more complete and accepted tectonic history of the Blue Mountain unit and Crescent terrane.

An additional comparison can be traced to two igneous exposures within both terranes that have been identified as ophiolites. In the CPW terrane, the Resurrection Peninsula (Fig. 7 and 8) is comprised of an Eocene aged ophiolite in depositional contact with the CPW terrane (this paper). It is a partially complete sequence starting with a gabbro base, sheeted dike center, and pillow basalt cap with interbedded clastic sediments (Kusky et al., 2004; Bradley et al.,2006). The southern region of Vancouver Island defines the most northern part of the Crescent terrane and is made up of the Metchosin Igneous Complex. The Metchosin Igneous Complex (Fig.22a-b) has been categorized as an Eocene aged ophiolite (Glassley 1974; Timpa et al. 2005) that under-thrusts a proposed part of the CPW terrane known as the Leech River complex (Cowan, 2003) along the Leech River Fault (Fig. 22c).

From east to west, the Metchosin ophiolite sequence begins with gabbros, sheeted dikes, and pillow basalts interbedded with clastic marine sediments(Fig.23a). A metamorphic petrographic analysis by Timpa et al. (2005) found a distinct variability in metamorphic grade across the Metchosin Igneous Complex. In the east, the metamorphic facies are classified as low grade prehnite-pumpellyite (<280°C) in the east up to high grade amphibolite (>420°C) in the west (Fig.23b; Timpa et al., 2005). Timpa found the metamorphic grades and locations were consistent with those found along the overlying Leech River Complex. From this, Timpa et al. (2005) concludes the Metchosin underthrusted the Leech River Complex after which both were structurally tilted before experiencing regional metamorphism recorded on the Leech River Complex at around

~51 Ma (Groome et al. 2003). Because of the structural tilt, an orographic effect has caused higher precipitation and erosion in the east. The increased erosion results in larger exhumation rates accounted for in the higher amphibolite grade metamorphic rocks exposed in the west. The same explanation has been proposed for the Wrangellia terrane located up north from the Metchosin that also exhibits western exposures of higher grade and presumably deeply exhumed metamorphic rocks (Timpa et al., 2005).

Results from the Raman spectroscopy analysis suggest that the younger Orca more outboard in the Prince William terrane reflect a general increase in annealed Precambrian grains (Fig.25). This trend could result from denudation of the source terrain that, over time, increases the depth at which rocks are exhumed. Increased depths imply higher temperatures and pressures that could fully anneal damaged grains. If the Orca Group within the CPW terrane does in fact show an increase in annealed grains due to an unroofing of the source area, then the Crescent terrane holds as a potential provenance. Thus far, the age of both terranes, timing of volcanism, similarities in lithologies, paleolatitudinal locations, and signatures of increasing exhumation provide evidence for the possibility of correlating the CPW terrane in south-central Alaska with the Crescent terrane in northern Washington.

Conclusions

The comparison of U/Pb detrital zircon and Raman spectroscopy results of the Resurrection Peninsula ophiolite and surrounding area provide new insights into the tectonic evolution of the Chugach and Prince William terranes. The first is the 57 Ma age yielded from clastic sediment that was interbedded with the ophiolite sequence (Fig.16a:RB12-04). This age confirms the previous U/Pb age obtained from a plagiogranite on the opposite side of the ophiolite (Nelson et al., 1989). The second refers to the U/Pb zircon age signals of the other three samples (RB12-01, RB12-02, RB12-08) collected from sediment adjacent to and above the ophiolite sequence. All three samples had maximum depositional ages between 60-61 Ma. After further statistical analysis, the Resurrection Bay area is part of the Orca Group within the Prince William terrane that provides two main conclusions: 1) the current boundary between the Chugach terrane and Prince William terrane is incorrectly mapped 2) the Resurrection Peninsula ophiolite is conformably overlain by the Orca Group and in depositional continuity with the accretionary wedge.

The first conclusion demands reinterpretations in the present geologic map of the Chugach-Prince William terranes (Fig.3). Currently, sediment surrounding the Resurrection Peninsula lies to the left of the Contact Fault and, as such, is part of the Upper Cretaceous Valdez Group that defines the Chugach terrane. The U/Pb data collected from this area reveal the sediment is part of the Paleocene-Eocene Orca Group within the Prince William terrane. The Contact Fault that defines the two terranes must be amended in order to include the Resurrection Bay area within the Prince William terrane. Though no further information can be provided for the exact placement of the fault, it must be relocated west of Seward, Alaska.

The second conclusion establishes the relationship between the Resurrection Peninsula ophiolite and the CPW accretionary wedge. These results validate paleomagnetic data from the Resurrection Peninsula ophiolite (Bol et al., 1992) that indicated formation at a paleolatitude 13 ± 9° south of its present location, supporting large coast-parallel translation of the entire CPW terrane during the Late Cretaceous through the Paleocene (Fig. 21b). Though the translation recorded for the ophiolite only covers the time between its formation and emplacement (~55 Ma), it reaffirms a more complete translation of the Chugach-Prince William terrane proposed in what has been termed the Baja BC hypothesis (Irving, 1985). For more information on the translation of the CPW terrane prior to the Eocene, refer to Cowan et al. (1997).

Under the proposed conditions, the hypothesis requires rapid slip to achieve the amount of coast-parallel translation in the short time interval. Therefore, the small age difference between the Ghost Rocks in Kodiak Island (~65 Ma) and the Resurrection Peninsula ophiolite (~55 Ma) makes a big difference in the expected/predicted position (Fig.21). The translation model suggests that during 55 Ma, the Resurrection ophiolite would be located off the present day coast of northern Washington (Fig.22). A potential provenance at this location (Fig.21b and 23b) combined with Raman spectroscopy results (Fig.25) predicts a source area conducive to increased annealing due to exhumation over time (Fig.23c). The results match with the timing of uplift, tilting, and subsequent exhumation occurring in the Crescent terrane that could have supplied grains of varying damage and thus metamorphic grades observed in the Precambrian grains of the Chugach-Prince William terrane. However, the credibility of this correlation remains contingent upon future research including obtaining and comparing U/Pb detrital zircon signals from this area and a more thorough understanding of its composition and formation.

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Figures

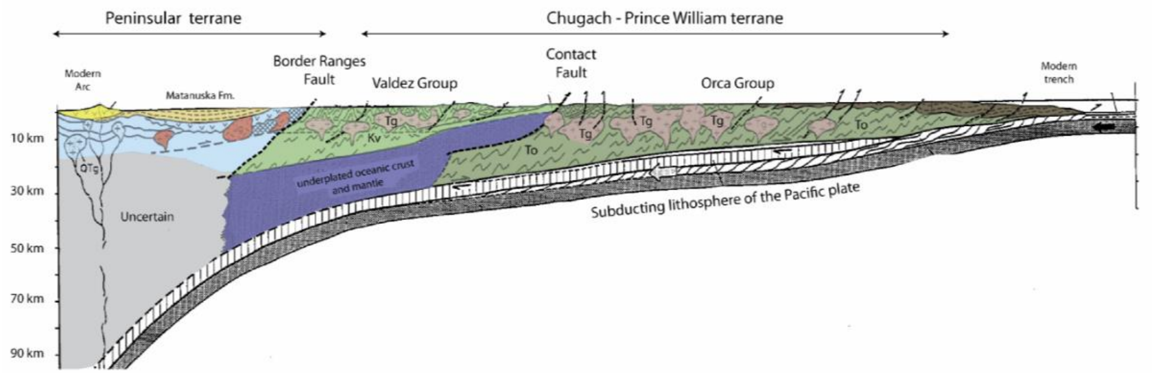


Figure 1: Cross-section of south-central Alaska showing 30 km thick accretionary wedge of Chugach-Prince William terrane with Sanak-Baranof Belt intrusions shown in pink. Wedge youngs outboard from Upper Cretaceous Valdez Group to Paleocene-Eocene Orca Group. Modified from Plafker et al. (1994).

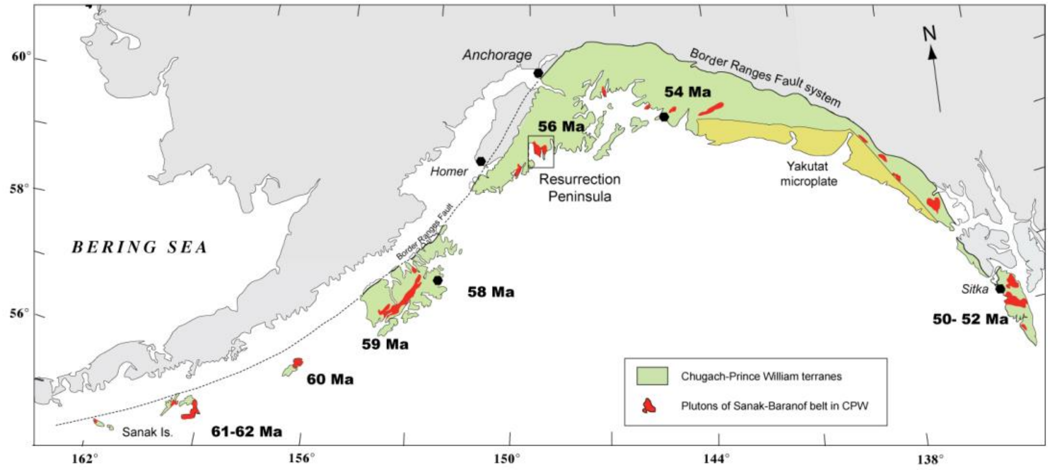


Figure 2: Geologic map of the southern margin of Alaska isolating the Chugach-Prince William terrane shown in green with red intrusions of the Sanak-Baranof Belt shown in red with corresponding ages (Pavlis and Roeske, 2007).

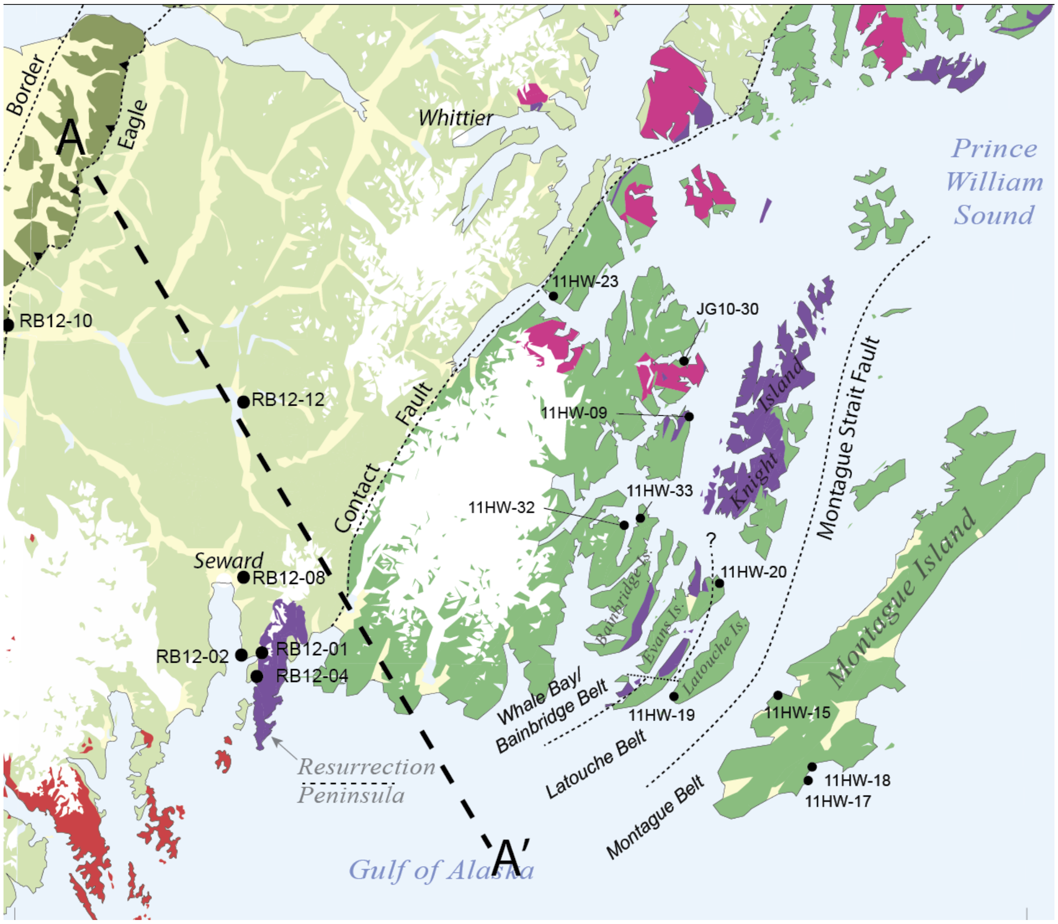


Figure 3: Study transect (A-A') projected along geologic map of Chugach-Prince William terrane. Sample locations indicated by black dots. Note current mapping of Contact Fault that defines boundary between Valdez Group of the Chugach terrane and the Orca Group of the Prince William terrane. Map modified from Bradley (2006) and Kveton (1989).

Figure 4: Deep marine flysch sequences that make up bulk of Chugach-Prince William terrane. Pictured outcrop is part of the Shumagin Formation, member of the Upper Cretaceous Valdez Group on Nagai Island in western region of Chugach terrane.

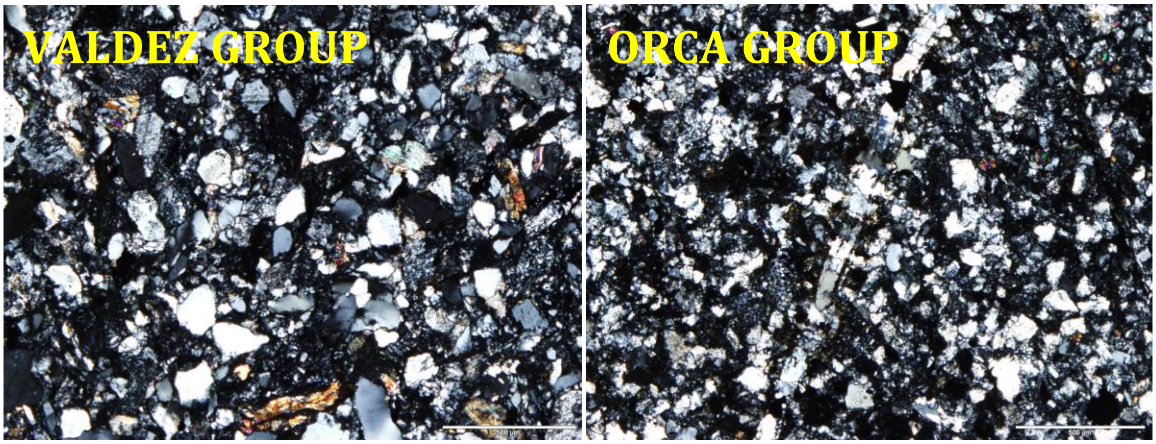


Figure 5: Polarized image of thin sections showing similar compositions between the Upper Cretaceous Valdez Group (left) and the Paleocene to Eocene Orca Group (right) that reinforces previous conclusions from petrographic studies (Dumoulin, 1977).

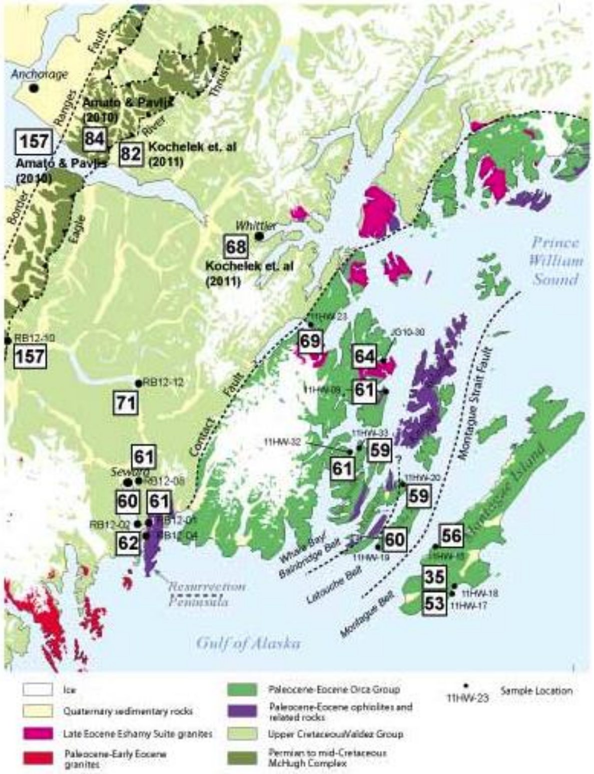


Figure 6: Geologic map of CPW modified from Bradley (2006) and Kveton (1989) showing all present U/Pb maximum depositional ages of the Chugach-Prince William terranes from this study, Valdez Group (Amato and Pavlis, 2010; Kochelek et al., 2011), and Orca Group (Hilbert-Wolf, 2012).

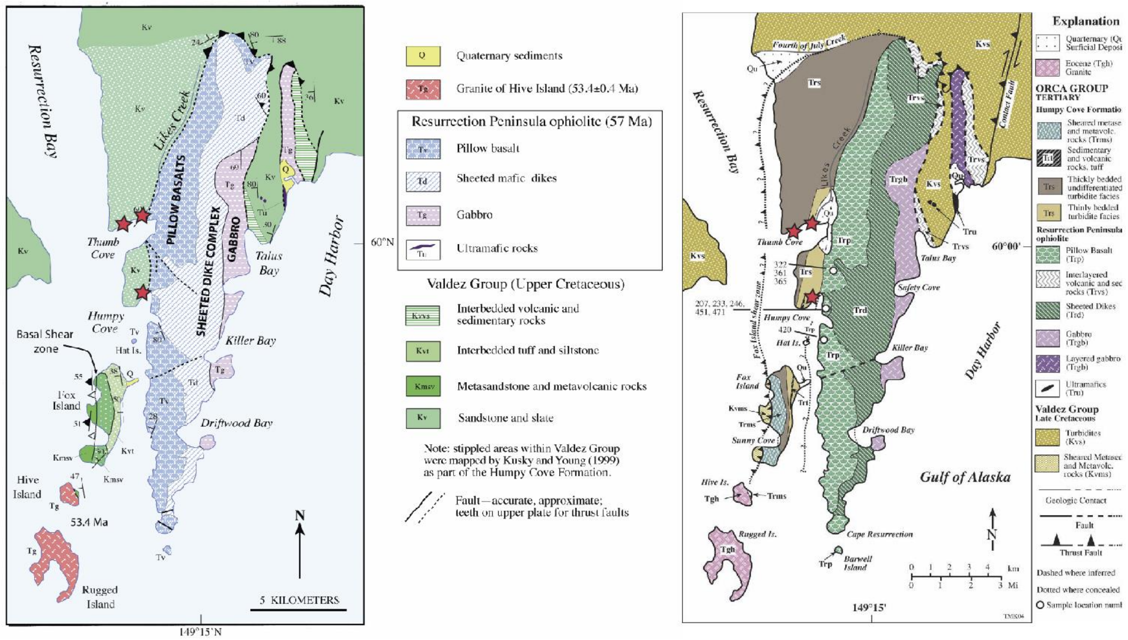


Figure 7: Two interpretations of western side of Resurrection Peninsula ophiolite. The map on the left (Bradley and Miller, 2006) interprets strata as Cretaceous aged Valdez Group, fault bounded, and unrelated to CPW terrane. The second map (Kusky and Young, 1999) defines the strata as Paleocene aged Orca Group from U/Pb zircon data. Based on this interpretation, the ophiolite is in depositional continuity with CPW terrane.

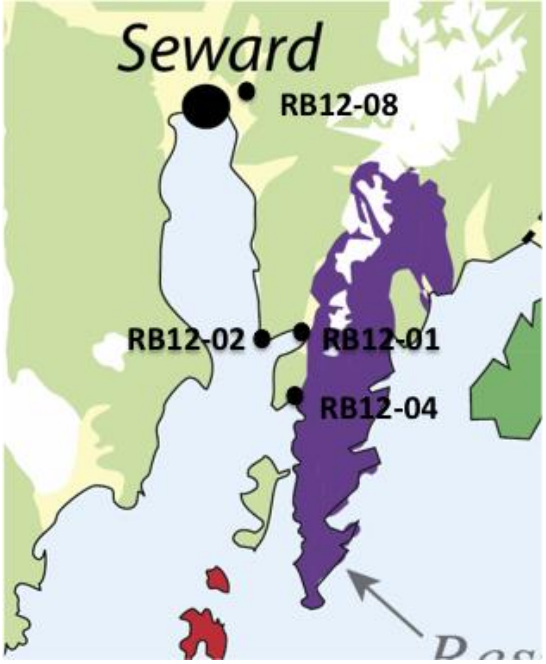


Figure 8: Detailed view of main study area: Resurrection Peninsula ophiolite in Resurrection Bay, Seward, Alaska. Four samples shown in black indicate localities in which U/Pb detrital zircon ages were obtained from strata interbedded with, adjacent to, and above the Resurrection Peninsula ophiolite. Geologic map modified from Kveton (1989) and Bradley (2006).

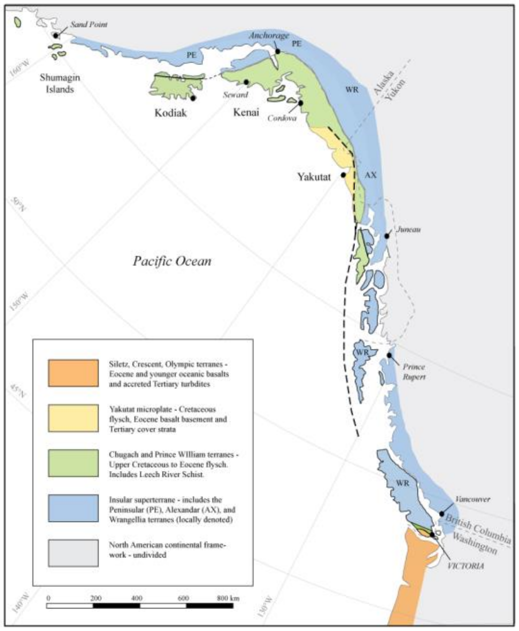


Figure 9: Geologic map from Cowan (2003) showing Southern Composite terrane including the a) Siletzia, Crescent, and Olympics (orange) b) Yakutat (yellow) c) CPW (green) d) Insular Superterrane: Peninsular, Alexander, and Wrangellia.

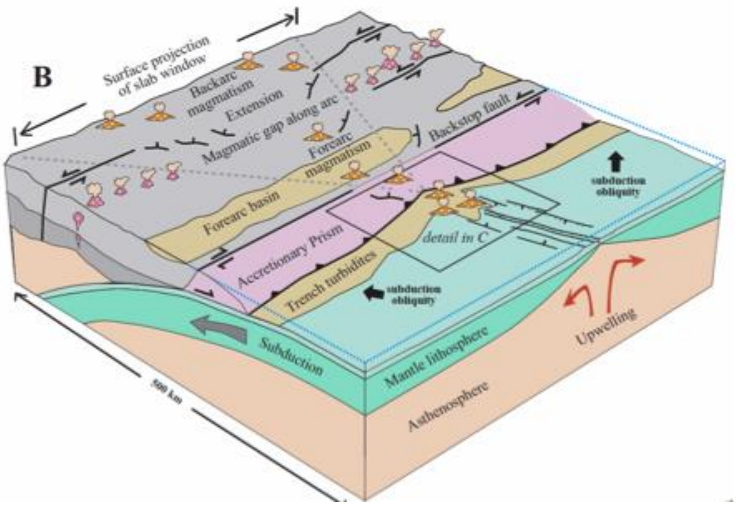


Figure 10: Figure from Bradley et al. (2006) showing generally accepted model for ophiolites and forearc magmatism in CPW in which a trench-ridge-trench (TRT) triple junction in which spreading center is subducted. Above shows interaction of slab window with overriding plate. The orange colored volanics are identified today as Sanak Baranof Belt and mid-ocean ridge buried with trench turbidites seen today in interbedded clastic sediment in pillow <u>basalts</u> of ophiolite.

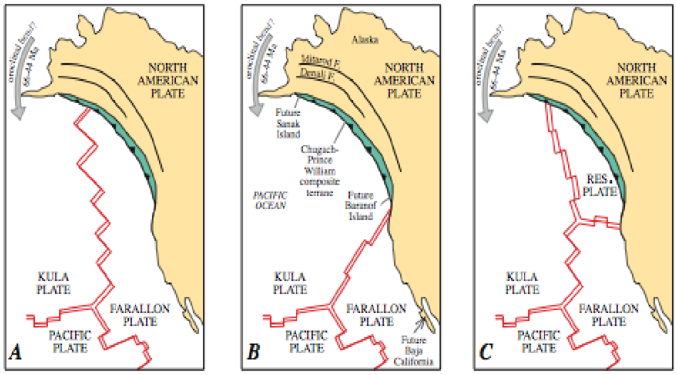


Figure 11: Proposed plate geometries for T-R-T triple junction: a) Kula-Farallon ridge subducted beneath CPW b) Kula-Farallon ridge subducted beneath Washington c) Additional Resurrection Plate generates two T-R-T triple junctions in which ophiolite formed approximately in-situ without translation. Figure from Bradley et al. (2006).

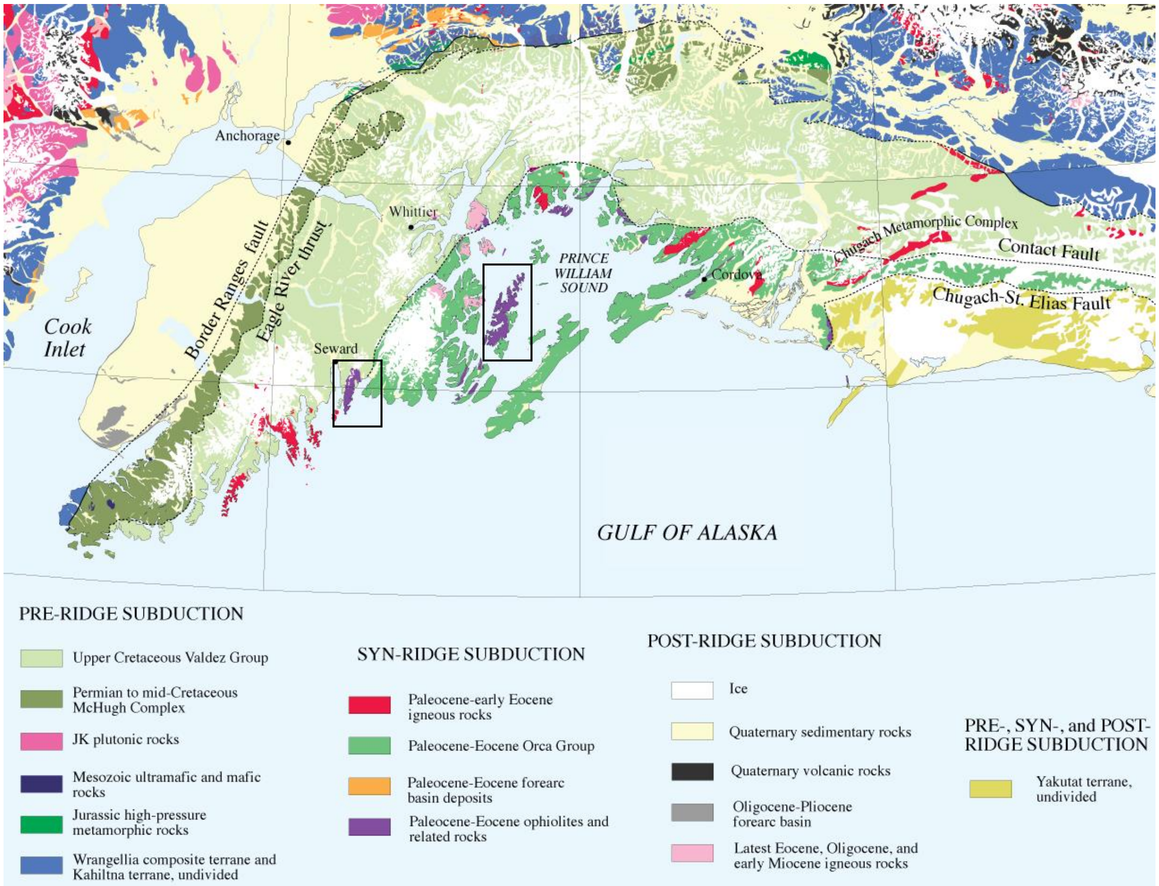


Figure 12: Geologic map modified from Plafker (1989) and Bradley (2006) showing full view of units within the Chugach-Prince William terrane younging outboard: McHugh Complex (dark green), Valdez Group (pale green), Orca Group (bright green). Resurrection and Knight Island ophiolite sequences outined in black boxes.

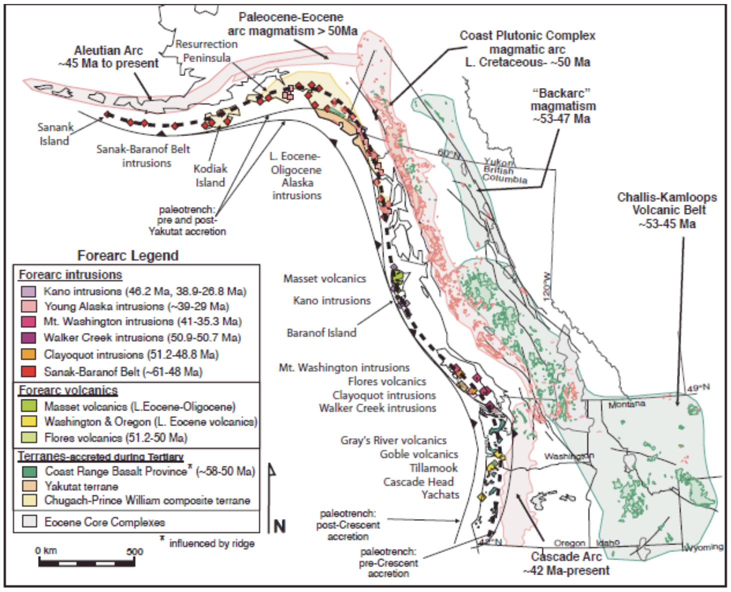


Figure 13: Map of Northern Cordillera highlighting the forearc magmatism with the Sanak-Baranof Belt and volcanics. Small igneous exposures are symbolized as diamonds and squares as seen on Kodiak Island just west of study area in Resurrection Peninsula. Map modified from Madsen et al. (2006) and Gallen (2008).

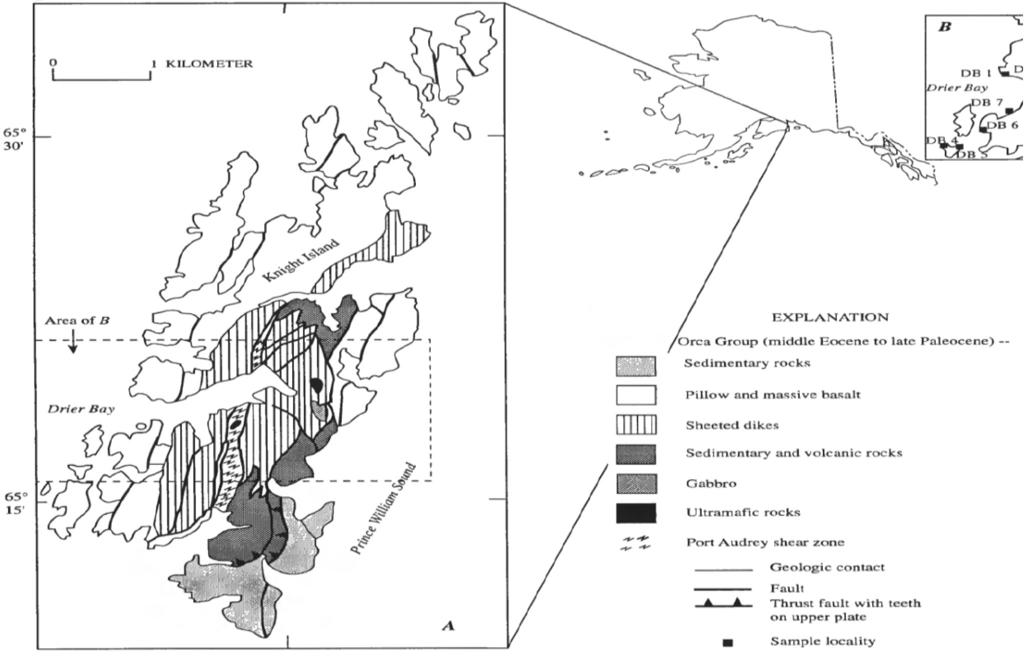


Figure 14: Simplified geologic map from Nelson and Nelson (1993). of Knight Island ophiolite in Prince William Sound located 85 km east of Resurrection ophiolite.

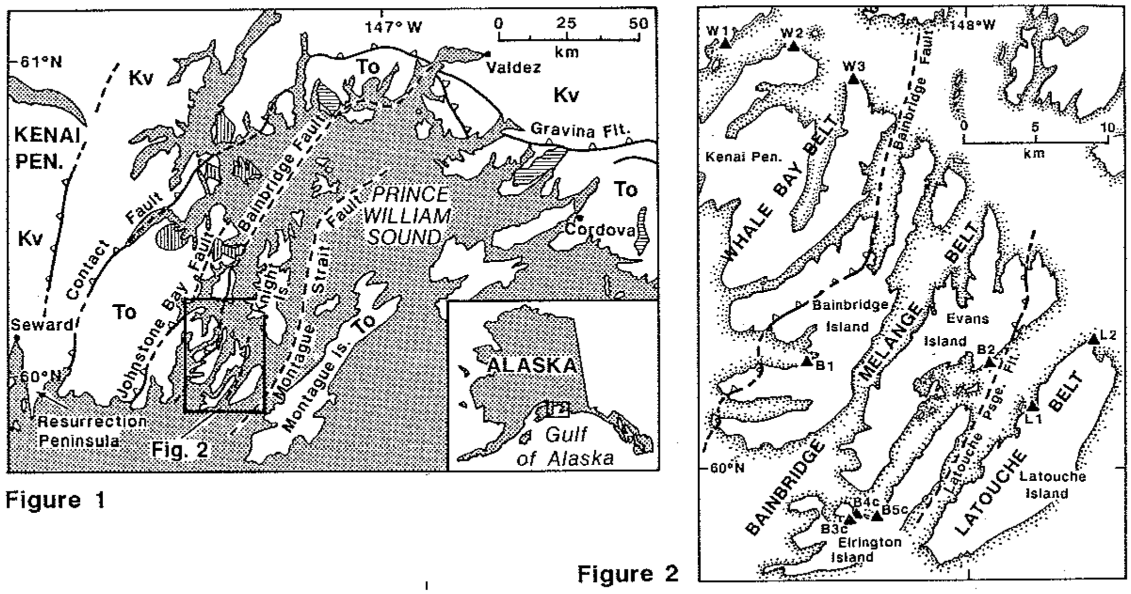
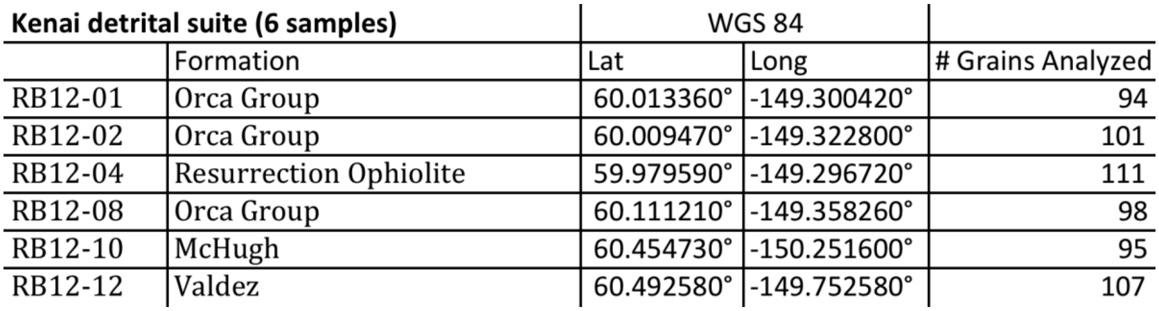


Figure 15: a) Geologic map from Kveton (1988) emphasizing structural contacts in Prince William Sound terrane b) Fault-bounded stratigraphic belts as defined by Kveton (1988) within Prince William Sound.

Figure 16: a) Location of sample RB12-04 from clastic sediment interbedded with pillow basalts located on the western contact side of the Resurrection Peninsula ophiolite. From this stratigraphic field relationship, the U/Pb detrital zircon ages that were obtained from the sample (57 Ma) more confidently define the age of the ophiolite. b) Similar lithologies and interbedded relationships present in Knight Island ophiolite.



Kenai detrital suite (6 samples)		WGS 84		
	Formation	Lat	Long	# Grains Analyzed
RB12-01	Orca Group	60.013360°	-149.300420°	94
RB12-02	Orca Group	60.009470°	-149.322800°	101
RB12-04	Resurrection Ophiolite	59.979590°	-149.296720°	111
RB12-08	Orca Group	60.111210°	-149.358260°	98
RB12-10	McHugh	60.454730°	-150.251600°	95
RB12-12	Valdez	60.492580°	-149.752580°	107

Figure 17: Table showing sample names, proposed group, longitude and latitude, and the number of grains analyzed for U/Pb in each sample.

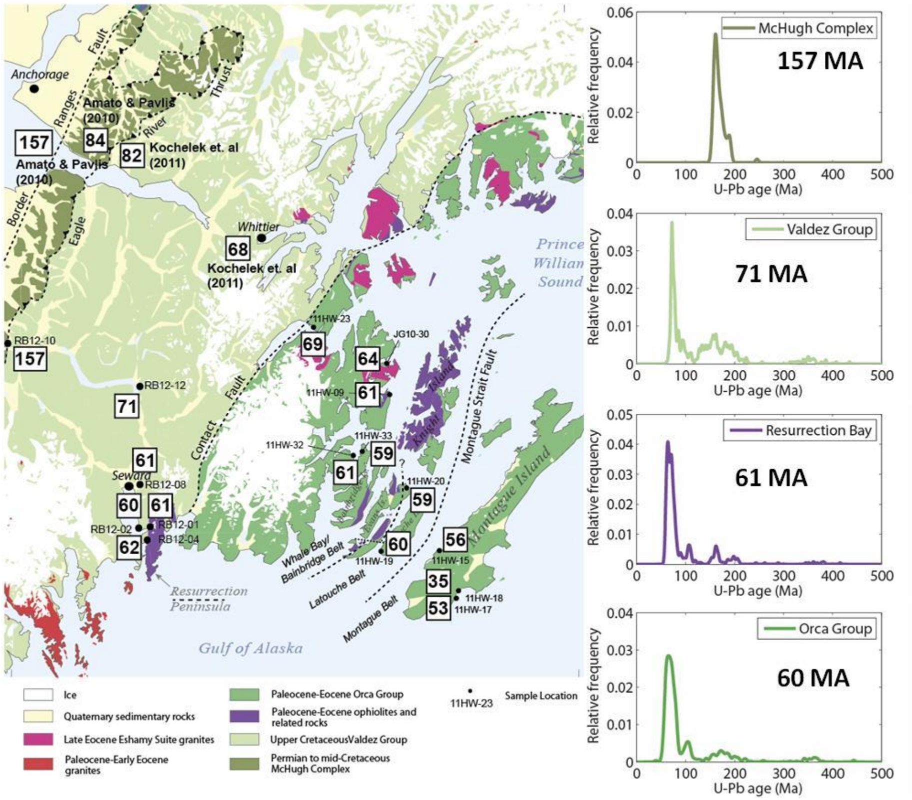


Figure 18: Unique U/Pb detrital signals collected along transect A-A' with color corresponding to position on geologic map modified from Bradley (2006) and Kveton (1989). Maximum depositional ages show McHugh Complex is most different from the rest of the CPW terrane

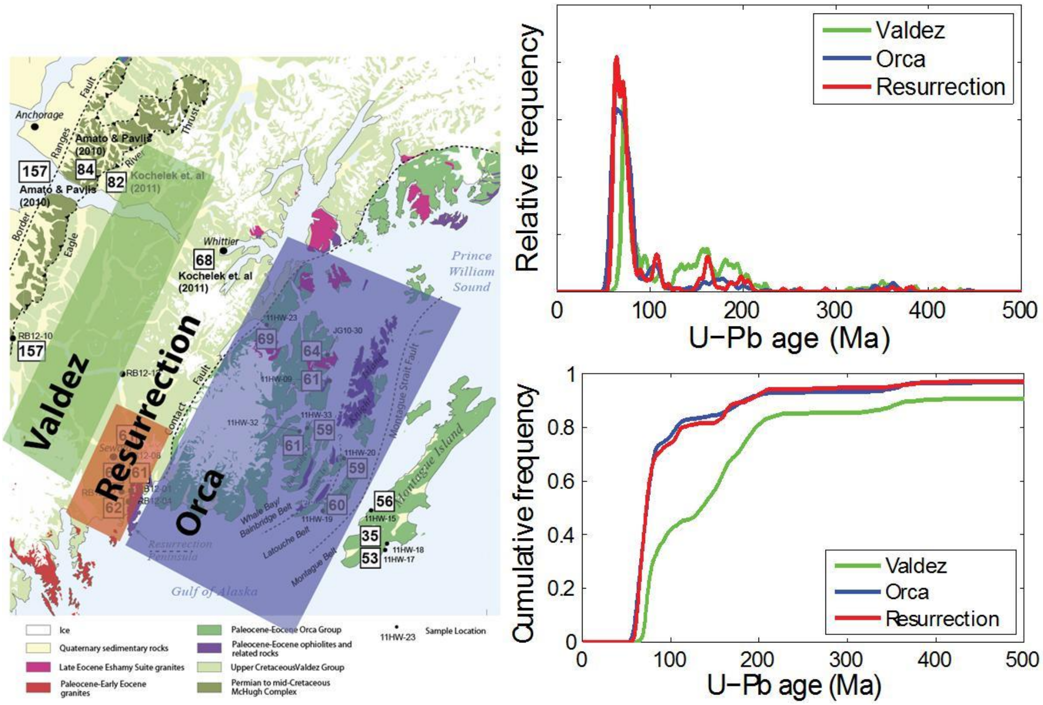


Figure 19: Determining the age and corresponding relationship between clastic strata adjacent to the ophiolite and the CPW terrane using a) PDP of U/Pb age distributions from RB, Valdez and Orca b) Cumulative frequency plots comparing differences in age populations. Resurrection Bay is most similar to the Paleocene-Eocene Orca Group.

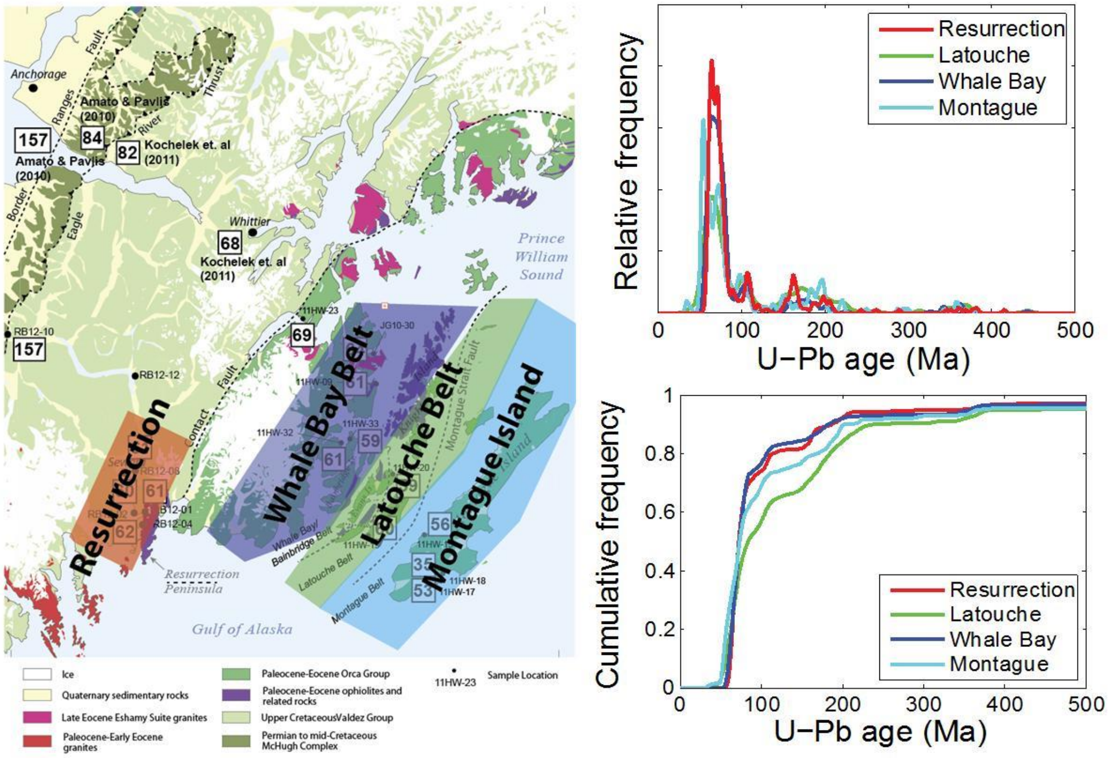


Figure 20: Geologic map of CPW modified from Bradley (2006) and Kveton (1989) with different colors indicating fault bounded belts within PWS Orca Group (Kveton,1989; Wolf 2012). Graphs correlating RB with adjacent Orca of fault-bounded belts in PWS: a) PDP of U/Pb age distributions from RB, Whale Bay, Latouche, and Montague Island. b) Cumulative frequency plots comparing differences in age populations. Resurrection Bay most similar to Whale Bay Belt that contains adjacent Knight Island ophiolite.

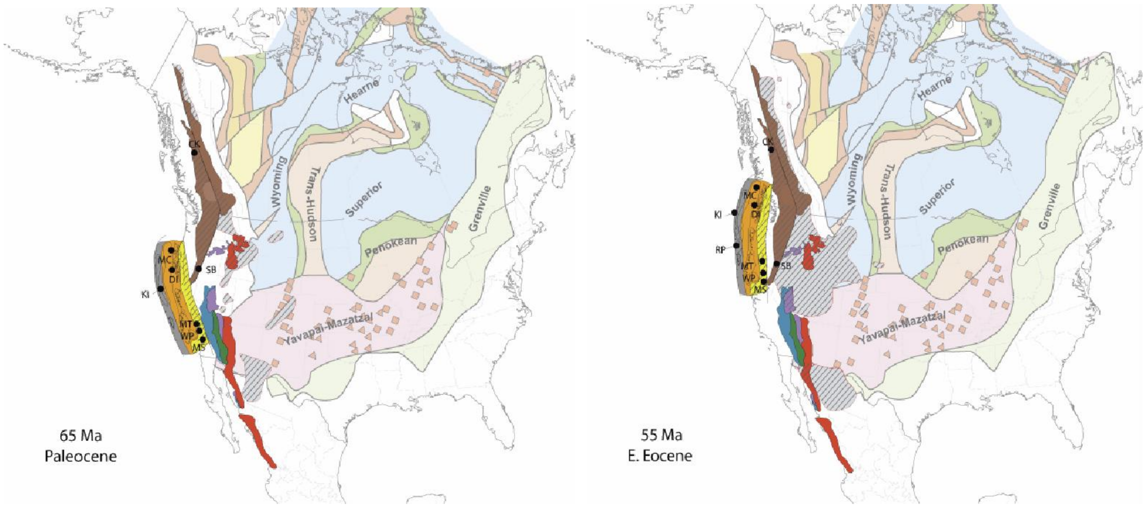


Figure 21: The two panels above are adapted from Miller et al. (2006) that detail the movement history of the Baja BC block. The figure includes permissive positions for the CPW based on new paleomagnetic results from a) Kodiak Island (~65 Ma) by Housen, Roeske, Galen and O'Connell and b) the Bol et al., result from the Resurrection Peninsula Ophiolite (~55Ma).

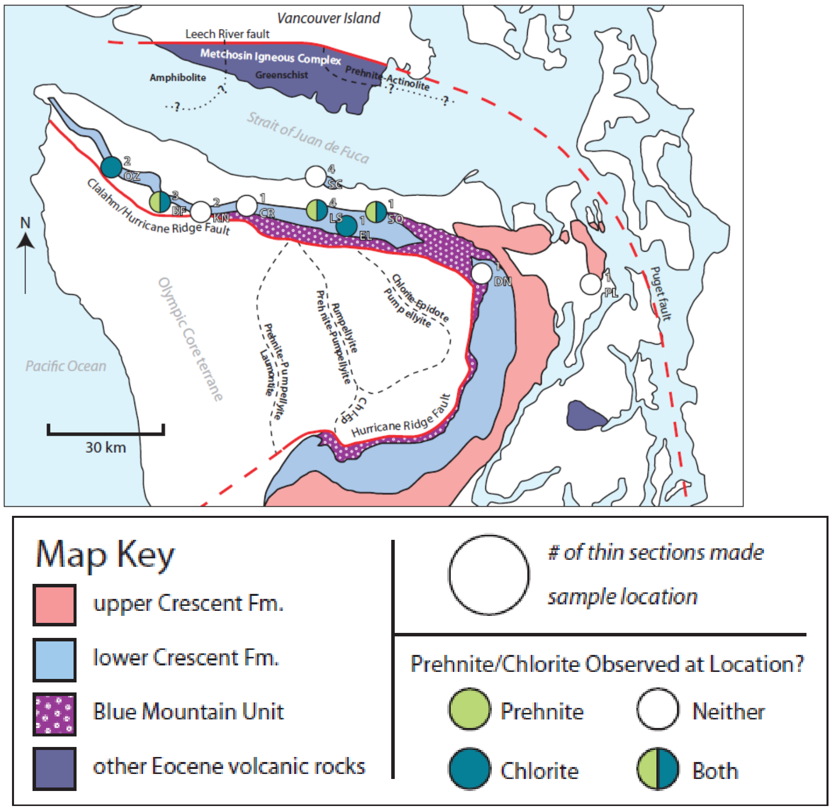


Figure 22: Geologic map of possible provenance for the CPW located off of the northern coast of Washington including the Crescent terrane and Olympic Core terrane. Map

shows stratigraphic relationship between basalts of the Paleocene-Eocene Crescent terrane that interbed and are underlain by deep marine sequences of the Blue Mountain Unit.

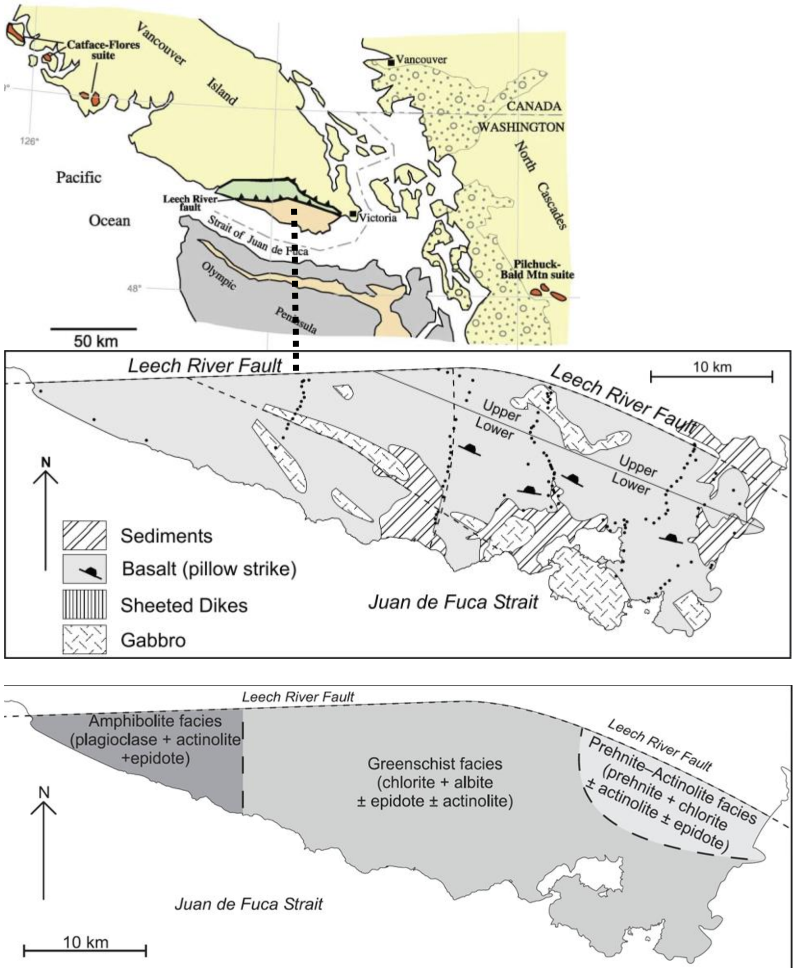


Figure 23: Locating a provenance using a) geologic map of northern Washington (Cowan, 2003) showing possible displaced block of CPW terrane juxtaposed with Metochsoin Igenous Complex of Coast Range terrane b) map of Metochosin Igneous Complex from Timpa et al. (2005) showing ophiolite sequence and c) increasing metamorphic grades.

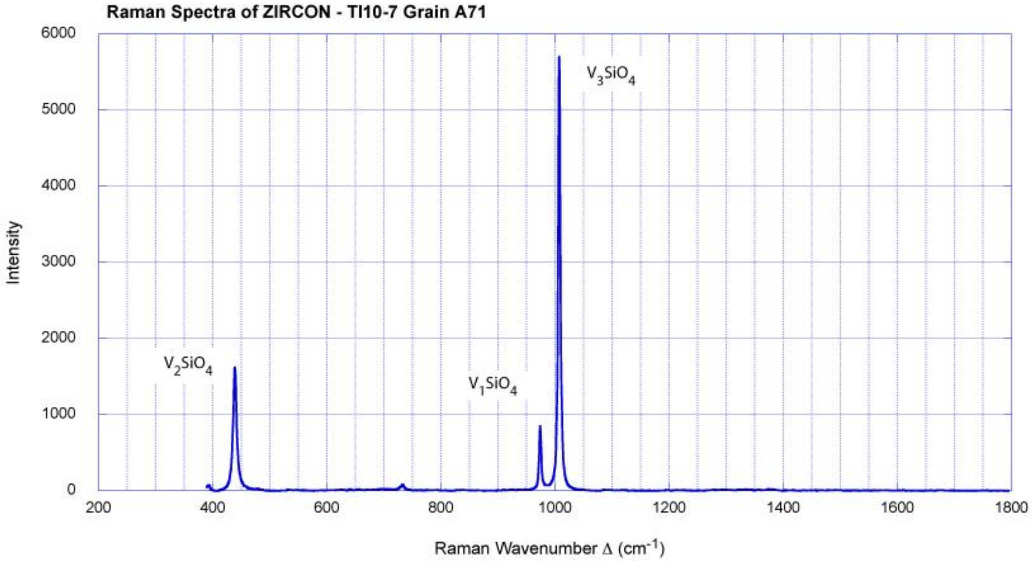


Figure 24: Plot from John Garver showing standard Raman wavenumbers for zircon grains that are fully annealed, undamaged grains.

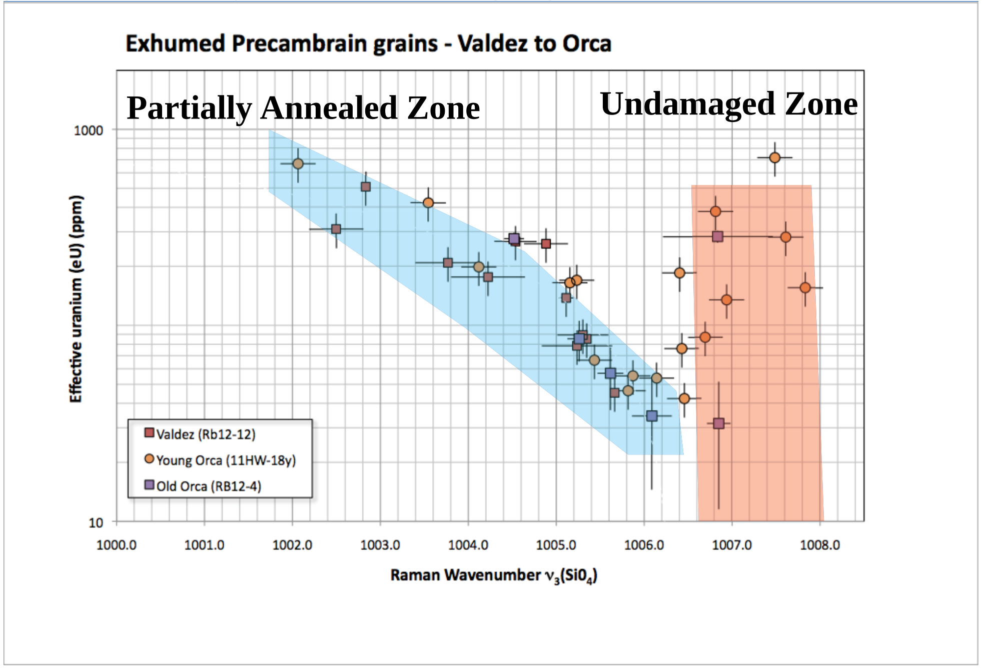


Figure 25: Raman spectroscopy results of Precambrian grains isolated from Upper Cretaceous Valdez, older Orca of the Resurrection ophiolite, and younger Orca from Montague Island showing gradual annealing in younging direction of CPW. Possible explanation could be exhuming source depositing grains of increasing metamorphic grade during terrane formation.

References

Amato, J.M., and Pavlis, T.L., 2010, Detrital zircon ages from the Chugach Terrane, Southern Alaska, reveal multiple episodes of accretion and erosion in a subduction complex: Geology [Boulder], v. 38, no. 5; 5, p. 459-462.

Babcock, R.S., Burmester, R.F., Engebretson, D.C., Warnock, A., and Clark, K.P., 1992, A rifted margin origin for the Crescent basalts and related rocks in the northern Coast Range volcanic province, Washington and British Columbia: Journal of Geophysical Research, v. 97, p. 6799-6821.

Bol, A.J., Coe, R.S., Gromme, C.S., and Hillhouse, J.W., 1992, Paleomagnetism of the Resurrection Peninsula, Alaska; implications for the tectonics of southern Alaska and the Kula-Farallon Ridge: Journal of Geophysical Research, v. 97, p. 17.

Bradley, D.C., and Miller, M.L., 2006, Field Guide to South-Central Alaska's Accretionary Complex: Anchorage to Seward: Alaska Geological Society, p. 1-32.

Bradley, D.C., Kusky, T.M., Haeussler, P.J., et al., 2003, Geologic signature of early Tertiary ridge subduction in Alaska: Special Paper - Geological Society of America, v. 371, p. 19-49.

Breitsprecher, K., Thorkelson, D.J., Groome, W.G., and Dostal, J., 2003, Geochemical confirmation of the Kula-Farallon slab window beneath the Pacific Northwest in Eocene time: Geology [Boulder], v. 31, no. 4; 4, p. 351-354.

Byrne, T., 1982, Structural evolution of coherent terranes in the Ghost Rocks Formation, Kodiak Island, Alaska: Special Publication - Geological Society of London, v. 10, p. 229-242.

Carlson, B.M., 2012,
Cooling and provenance revealed through detrital zircon fission track dating of the Upper Cretaceous Valdez group and Paleogene Orca Group in western Prince William Sound, Alaska; Proceedings from the 25th Annual Keck Geology Consorptium Undergraduate Research Symposium, Amherst, MA. , v. 25.

Case, J.E., Barnes, D.F., Plafker, G., and Robbins, S.L., 1966, Gravity survey and regional geology of the Prince William Sound epicentral region, Alaska, C1 p.

Case, J.E., Sikora, R., Tysdal, R.G., Barnes, D.F., and Morin, R., 1979, Geologic interpretation of the gravity anomaly map of the Seward and Blying Sound quadrangles, Alaska: United States, U. S. Geological Survey : Reston, VA, United States.

Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis; subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts: Geological Society of America Bulletin, v. 105, no. 6; 6, p. 715-737.

Cowan, D.S., 2003, Revisiting the Baranof-Leech River hypothesis for early Tertiary coastwise transport of the Chugach-Prince William Terrane: Earth and Planetary Science Letters, v. 213, no. 3-4; 3-4, p. 463-475.

Cowan, D.S., Brandon, M.T., and Garver, J.I., 1997, Geological tests of hypotheses for large coastwise displacements; a critique illustrated by the Baja British Columbia controversy: American Journal of Science, v. 297, no. 2; 2, p. 117-173.

Denny, A.C., 2012, Geochemistry of the Lower Crescent Formation, Washington, and Reevaluation of Proposed Formation Hypotheses: Senior Integrative Exercise, no. Carleton College, Northfield, Minnesota.

Dumoulin, J.A., 1987, Sandstone composition of the Valdez and Orca groups, Prince William Sound, Alaska.

Duncan, R.A., 1981, A captured island chain in the Coast Range, Oregon and Washington: EOS, Transactions, American Geophysical Union, v. 62, no. 45; 45, p. 1028-1028.

Dusel-Bacon, C., Csejtey, B., Jr., Foster, H.L., Doyle, E.O., Nokleberg, W.J., and Plafker, G., 1993, Distribution, facies, ages, and proposed tectonic associations of regionally metamorphosed rocks in east- and south-central Alaska, C1 p.

Dusel-Bacon, C., Doyle, E.O., and Box, S.E., 1996, Distribution, facies, ages, and proposed tectonic associations of regionally metamorphosed rocks in Southwestern Alaska and the Alaska Peninsula, B1 p.

Enkelmann, E., Garver, J.I., and Pavlis, T.L., 2008, Rapid exhumation of ice-covered rocks of the Chugach-St. Elias Orogen, southeast Alaska: Geology [Boulder], v. 36, no. 12; 12, p. 915-918.

Farris, D.W., Haeussler, P., Friedman, R., Paterson, S.R., Saltus, R.W., and Ayuso, R., 2006, Emplacement of the Kodiak Batholith and slab-window migration: Geological Society of America Bulletin, v. 118, no. 11-12; 11-12, p. 1360-1376.

Gallen, S.F., 2008, An investigation of the magnetic fabrics and paleomagnetism of the Ghost Rocks Formation, Kodiak Islands, Alaska.

Garver, J.I., Davidson, C.M., DeLuca, M.J, Pettiette, R.A., Roe, C.F., and Hilbert-Wolf, H., 2013. Constraints of the original setting of the flysch of the Chugach and Prince William terranes in Alaska using detrital zircon. 2013 Cordilleran tectonics workshop, Kingston Ontario, Abstracts with Program, p. 21-23.

Gehrels, G.E., Rusmore, M., Woodsworth, G., Crawford, M., Adronicos, C., Hollister, L., Patchett, J., Ducea, M., Butler, R., Klepeis, K., Davidson, C., Friedman, R., Haggart, J., Mahone, B., Crawford, D., Pearson, D., and Girardi, J., 2009, U-Th-P geochronology of the Coast Mountains batholith in north-coastal British Columbia: constraints on age and tectonic evolution: GSA Bulletin 121, p. 1341-1361.

Glassley, W., 1974, Geochemistry and Tectonics of the Crescent Volcanic Rocks, Olympic Peninsula, Washington: Geological Society of America Bulletin, v. 85, no. 5; 5, p. 785-794.

Gromme, C.S., and Hillhouse, J.W., 1981, Paleomagnetic evidence for northward movement of the Chugach Terrane, southern and southeastern Alaska, 70 p.

Haeussler, P.J., Bradley, D.C., Wells, R.E., and Miller, M.L., 2003, Life and death of the Resurrection Plate; evidence for its existence and subduction in the northeastern Pacific in Paleocene-Eocene time: Geological Society of America Bulletin, v. 115, no. 7; 7, p. 867-880.

Hilbert-Wolf, H.L., 2012, U/Pb detrital zircon provenance of the flysch of the Paleogene Orca Group, Chugach-Prince William terrane, Alaska; Proceedings from the 25th Keck Geology Consorptium Undergraduate Research Symposium, Amherst, MA., v. 25.

Hudson, T., Plafker, G., and Peterman, Z.E., 1979, Paleogene anatexis along the Gulf of Alaska margin: Geology [Boulder], v. 7, no. 12; 12, p. 573-577.

Hudson, T.L., Arth, J.G., Winkler, G.R., and Stern, T.W., 1985, Jurassic plutonism along the Gulf of Alaska: Abstracts with Programs - Geological Society of America, v. 17, no. 6; 6, p. 362-362.

Hudson, T.L., 1986, Plutonism and provenance; implications for sandstone compositions, 55 p.

Hudson, T., and Arth, J.G., 1983, Tin granites of Seward Peninsula, Alaska: Geological Society of America Bulletin, v. 94, no. 6; 6, p. 768-790.

Johnson, E., 2012, Origin of Late Eocene granitiods in western Prince William Sound, Alaska; Proceedings from the 25th Keck Geology Consortium Undergraduate Research Symposium, Amherst MA., v. 25.

Jones, D.L., Silberling, N.J., and Hillhouse, J., 1977, Wrangellia; a displaced terrane in northwestern North America: Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre, v. 14, no. 11; 11, p. 2565-2577.

Jones, D.L., Silberling, N.J., Coney, P.J., and Plafker, G., 1984, Lithotectonic terrane map of Alaska (west of the 141st meridian), A1 p.

Kochelek, E.J., Amato, J.M., Pavlis, T.L., and Clift, P.D., 2011, Flysch deposition and preservation of coherent bedding in an accretionary complex; detrital zircon ages from the Upper Cretaceous Valdez Group, Chugach Terrane, Alaska: Lithosphere, v. 3, no. 4; 4, p. 265-274.

Kveton, K.J., 1989, Structure, thermochronology, provenance, and tectonic history of the Orca Group in southwestern Prince William South, Alaska [Ph.D. thesis]: University of Washington, p.184-186.

Kusky, T.M., Ganley, R., Lytwyn, J., and Polat, A., 2004, The Resurrection Peninsula ophiolite, melange and accreted flysch belts of southern Alaska as an analog for trench-forearc systems in Precambrian orogens: Developments in Precambrian Geology, v. 13, p. 627-674.

Kusky, T.M., and Young, C.P., 1999, Emplacement of the resurrection Peninsula ophiolite in the southern Alaska Forearc during a ridge-trench encounter: Journal of Geophysical Research, v. 104, p. 29.

Kveton, K.J., 1988, Bearing of fission-track dates on the structure and geologic history of the Orca Group accretionary prism, southern Alaska: EOS, Transactions, American Geophysical Union, v. 69, no. 44; 44, p. 1452-1452.

Lytwyn, J.N., Casey, J., Gilbert, S., and Kusky, T.M., 1997, Arc-like mid-ocean ridge basalt formed seaward of a trench-forearc system just prior to ridge subduction; an example from subaccreted ophiolites in Southern Alaska: Journal of Geophysical Research, v. 102, p. 10.

Marsellos, A.E., and Garver, J.I., 2010, Radiation damage and uranium concentration in zircon as assessed by Raman spectroscopy and neutron irradiation: American Mineralogist, v. 95, no. 8-9; 8-9, p. 1192-1201.

Miller, I.M., Brandon, M.T., and Hickey, L.J., 2006, Using Leaf Margin Analysis to Estimate the Mid-Cretaceous (Albian) Paleoaltitude of the Baja BC Block: Earth and Planetary Science Letters, no. 245, p. 95-114.

Nelson, S.W., Miller, M.L., and Dumoulin, J.A., 1987, Resurrection Peninsula and Knight Island ophiolites and recent faulting on Montague Island, southern Alaska Centennial field guide. *in* : United States, Geol. Soc. Am. : Boulder, CO, United States 1, p.433-438.

Nelson, S.W., Miller, M.L., and Dumoulin, J.A., 1989, The Resurrection Peninsula ophiolite, in Nelson, S.W., and Hamilton, T.D., eds., Guide to the Geology of the

Resurrection Bay- Eastern Kenai Fjords area, Alaska Guidebook. Geological Society of Alaska, Anchorage, p. 10-20.

Nelson, S.W., and Nelson, M.S., 1993, Geochemistry of ophiolitic rocks from Knight Island, Prince William Sound, Alaska, 130 p.

Nilsen, T.H., and Zuffa, G.G., 1982, The Chugach Terrane, a Cretaceous trench-fill deposit, southern Alaska: Special Publication - Geological Society of London, v. 10, p. 213-227.

O'Connell, K., Housen, B.A., and Roeske, S.M., 2007, Revisiting the paleomagnetism of a Paleocene trench-ridge-trench triple junction; Kodiak Islands, Alaska: Abstracts with Programs - Geological Society of America, v. 39, no. 4; 4, p. 7-7.

Plafker, G., and Lanphere, M.A., 1974, Age of the Bagley fault, in carter, Claire (e.d.): U.S. Geological Survey Alaska Program, v. U.S. geol. Survey Circ., no. 700, p. 52.

Plafker, G., Keller, G., Barron, J.A., and Blueford, J.R., 1985, Paleontologic data on the age of the Orca Group, Alaska.

Plafker, G., Moore, J.C., and Winkler, G.R., 1994, Geology of the southern Alaska margin, in Plafker, G., and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geol. Soc. Of America, The Geology of North America, v. G-1,p. 389-449.

Plumley, P.W., Coe, R.S., Byrne, T., 1983. Paleomagnetism of the Paleocene Ghost Rocks Formation, Prince William Terrane, Alaska. Tectonics 2, 295-314.

Press, W. H.; Flannery, B. P.; Teukolsky, S. A.; and Vetterling, W. T. *Numerical Recipes in FORTRAN: The Art of Scientific Computing, 2nd ed.* Cambridge, England: Cambridge University Press, p. 621, 1992.

Pyle, D.G., Duncan, R., Wells, R.E., Graham, D.W., Harrison, B., and Hanan, B.B., 2009, Siletzia; an oceanic large igneous province in the Pacific Northwest: Abstracts with Programs - Geological Society of America, v. 41, no. 7; 7, p. 369-369.

Ridgway, K.D., and Flesch, L.M., 2007, Cenozoic tectonic processes along the Southern Alaska convergent margin: Geology [Boulder], v. 35, no. 11; 11, p. 1055-1056.

Saltus, R.W., Hudson, T.L., and Connard, G.G., 1999, A new magnetic view of Alaska: GSA Today, v. 9, no. 3; 3, p. 1-6.

Simpson, R.W., J., 1977, Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range.

Sisson, V.B., Hollister, L.S., and Onstott, T.C., 1989, Petrologic and age constraints on the origin of a low-pressure/high-temperature metamorphic complex, southern Alaska: Journal of Geophysical Research, v. 94, p. 4392-4410.

Timpa, S., Gillis, K.M., and Canil, D., 2005, Accretion-related metamorphism of the Metchosin igneous complex, southern Vancouver Island, British Columbia: Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre, v. 42, no. 8; 8, p. 1467-1479.

Tysdal, R.G., Case, J.E., Winkler, G.R., and Clark, S.H.B., 1977, Sheeted dikes, gabbro, and pillow basalt in flysch of coastal southern Alaska: Geology [Boulder], v. 5, no. 6; 6, p. 377-383.

Tysdal, R.G., and Case, J.E., 1979, Geologic map of the Seward and Blying Sound quadrangles, Alaska: U.S. Geological Survey Miscellaneous Investigations Map I-1150, 12 p., scale 1:250,000.

Weinberger, J., and Sisson, V.B., 2003, Pressure and temperature conditions of brittle-ductile vein emplacement in the greenschist facies, Chugach metamorphic complex, Alaska; evidence from fluid inclusions: Special Paper - Geological Society of America, v. 371, p. 217-235.

Wells, R.E., Engebretson, D.C., Snavely, P.D., J., and Coe, R.S., 1984, Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington: Tectonics, v. 3, no. 2; 2, p. 275-294.

Winkler, G.R., Miller, M.L., Hoekzema, R.B., and Dumoulin, J.A., 1984, Guide to the bedrock geology of a traverse of the Chugach Mountains from Anchorage to Cape Resurrection: United States, Alaska Geol. Soc. : Anchorage, AK, United States.

Zumsteg, C.L., Himmelberg, G.R., Karl, S.M., and Haeussler, P.J., 2003, Metamorphism within the Chugach accretionary complex on southern Baranof Island, Southeastern Alaska: Special Paper - Geological Society of America, v. 371, p. 253-267.