Life and death of the Resurrection plate: Evidence for its existence and subduction in the northeastern Pacific in Paleocene–Eocene time

Peter J. Haeussler[†]
Dwight C. Bradley
U.S. Geological Survey, 4200 University Drive, Anchorage, Alaska 99508, USA
Ray E. Wells
U.S. Geological Survey, 345 Middlefield Drive, Menlo Park, California 95064, USA
Marti L. Miller
U.S. Geological Survey, 4200 University Drive, Anchorage, Alaska 99508, USA

ABSTRACT

Onshore evidence suggests that a plate is missing from published reconstructions of the northeastern Pacific Ocean in Paleocene–Eocene time. The Resurrection plate, named for the Resurrection Peninsula ophiolite near Seward, Alaska, was located east of the Kula plate and north of the Farallon plate. We interpret coeval near-trench magmatism in southern Alaska and the Cascadia margin as evidence for two slab windows associated with trench-ridge-trench (TRT) triple junctions, which formed the western and southern boundaries of the Resurrection plate. In Alaska, the Sanak-Baranof belt of near-trench intrusions records a west-to-east migration, from 61 to 50 Ma, of the northern TRT triple junction along a 2100-km-long section of coastline. In Oregon, Washington, and southern Vancouver Island, voluminous basaltic volcanism of the Siletz River Volcanics, Crescent Formation, and Metchosin Volcanics occurred between ca. 66 and 48 Ma. Lack of a clear age progression of magmatism along the Cascadia margin suggests that this southern triple junction did not migrate significantly. Synchronous near-trench magmatism from southeastern Alaska to Puget Sound at ca. 50 Ma documents the middle Eocene subduction of a spreading center, the crest of which was subparallel to the margin. We interpret this ca. 50 Ma event as recording the subduction-zone consumption of the last of the Resurrection plate.

The existence and subsequent subduction of the Resurrection plate explains (1) northward terrane transport along the southeastern Alaska–British Columbia margin between 70 and 50 Ma, synchronous with an eastward-migrating triple junction in southern Alaska; (2) rapid uplift and voluminous magmatism in the Coast Mountains of British Columbia prior to 50 Ma related to subduction of buoyant, young oceanic crust of the Resurrection plate; (3) cessation of Coast Mountains magmatism at ca. 50 Ma due to cessation of subduction, (4) primitive mafic magmatism in the Coast Mountains and Cascade Range just after 50 Ma, related to slab-window magmatism, (5) birth of the Queen Charlotte transform margin at ca. 50 Ma, (6) extensional exhumation of high-grade metamorphic terranes and development of core complexes in British Columbia, Idaho, and Washington, and extensional collapse of the Cordilleran foreland fold-and-thrust belt in Alberta, Montana, and Idaho after 50 Ma related to initiation of the transform margin, (7) enigmatic 53–45 Ma magmatism associated with extension from Montana to the Yukon Territory as related to slab breakup and the formation of a slab window, (8) right-lateral margin-parallel strike-slip faulting in southern and western Alaska during Late Cretaceous and Paleocene time, which cannot be explained by Farallon convergence vectors, and (9) simultaneous changes in Pacific-Farallon and Pacific-Kula plate motions concurrent with demise of the Kula-Resurrection Ridge.

Keywords: tectonics, Eocene, Kula plate, Farallon plate, North America, magmatism.

INTRODUCTION

Marine magnetic anomalies in the northern Pacific provide evidence for the existence of three plates and their associated spreading ridges during the early Tertiary: the Kula, Farallon, and Pacific plates (Atwater, 1970; Grow and Atwater, 1970). However, subduction of a critical part of the anomaly record beneath North America destroyed what would be the most straightforward evidence for (1) the geometry of the Kula-Farallon Ridge; (2) the location of its intersection with the continental margin, and (3) the possible existence of other ridges and plates in the region. The onshore geologic record is the sole remaining source of evidence for these features.

Along the northeast Pacific margin, geologists have long suggested that interactions with the Kula-Farallon Ridge could explain unusual near-trench Paleocene–Eocene magmatism both in southern Alaska and the Washington and Oregon coastal ranges—regions separated by >4000 km (Figs. 1, 2). In the Cascadia margin of coastal Oregon, Washington, and southern Vancouver Island, geologists proposed that intersection of the Kula-Farallon Ridge with the continental margin (Fig. 1A)

[†]E-mail: pheuslr@usgs.gov.

GSA Bulletin; July 2003; v. 15; no. 7; p. 867–880; 7 figures.

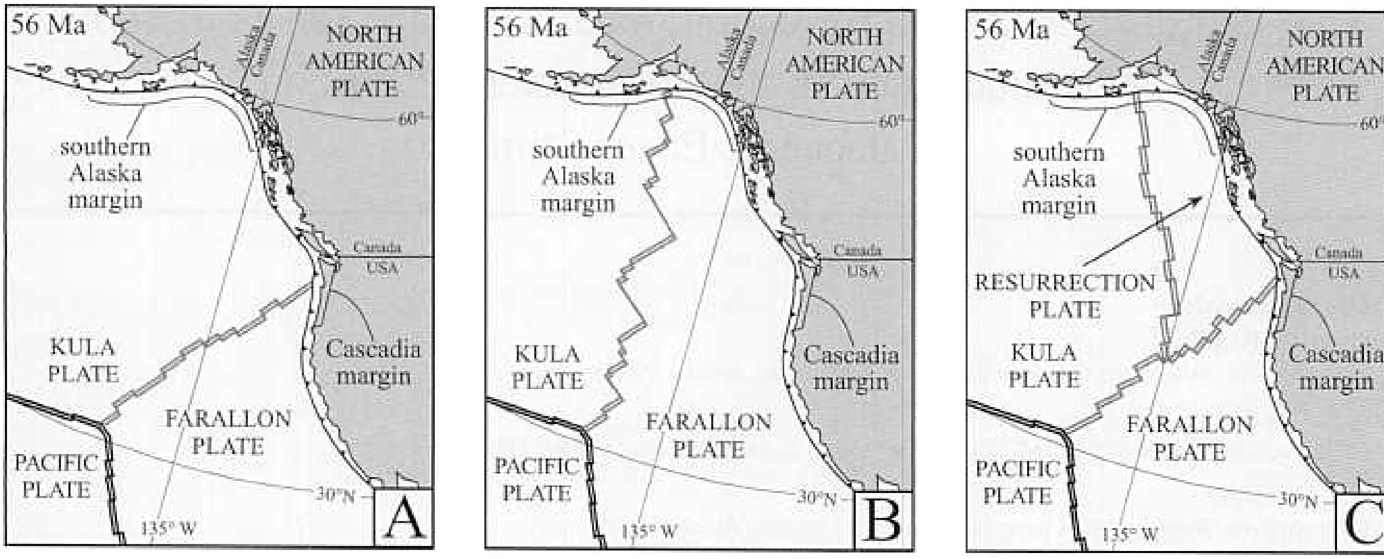


Figure 1. Plate geometries proposed to explain the latest Cretaceous to early Tertiary near-trench magmatic record of western North America at Chron 25 time (56.1 Ma). The orientation and geometry of spreading ridges in gray are speculative. (A) Kula-Farallon TRT triple junction would explain near-trench magmatism along the Cascadia margin, but not in southern Alaska. (B) Kula-Farallon TRT triple junction would explain near-trench magmatism in southern Alaska, but not along the Cascadia margin. (C) Two TRT triple junctions, one in southern Alaska and another along the Cascadia margin, indicate the presence of an additional oceanic plate—the Resurrection plate. This is the hypothesis we prefer and explore in this paper.

produced the oceanic basalt basement of the Coast Ranges (Fig. 2; e.g., Simpson and Cox, 1977; Duncan, 1982; Wells et al., 1984; Engebretson et al., 1985; Davis and Plafker, 1986; Thorkelson and Taylor, 1989; Babcock et al., 1992). Other workers, however, proposed that the Kula-Farallon Ridge intersected the southern Alaska margin at the same time (Fig. 1B), where it was responsible for granitic near-trench intrusions and high-temperature, low-pressure metamorphism (Marshak and Karig, 1977; Helwig and Emmett, 1981; Sisson et al., 1989; Bol et al., 1992; Bradley et al., 1993; Sisson and Pavlis, 1993; Haeussler et al., 1995; Pavlis and Sisson, 1995).

The same trench-ridge-trench (TRT) triple junction cannot explain the simultaneous near-trench magmatism of both areas. In this paper, we summarize the geologic evidence from coastal southern Alaska and the Pacific Northwest for the presence of two coeval TRT triple junctions. This circumstance implies the existence of an additional oceanic plate in the Pacific Ocean basin in Paleocene–Eocene time (Fig. 1C).

RECORD OF NEAR-TRENCH MAGMATISM

The Southern Alaska Margin

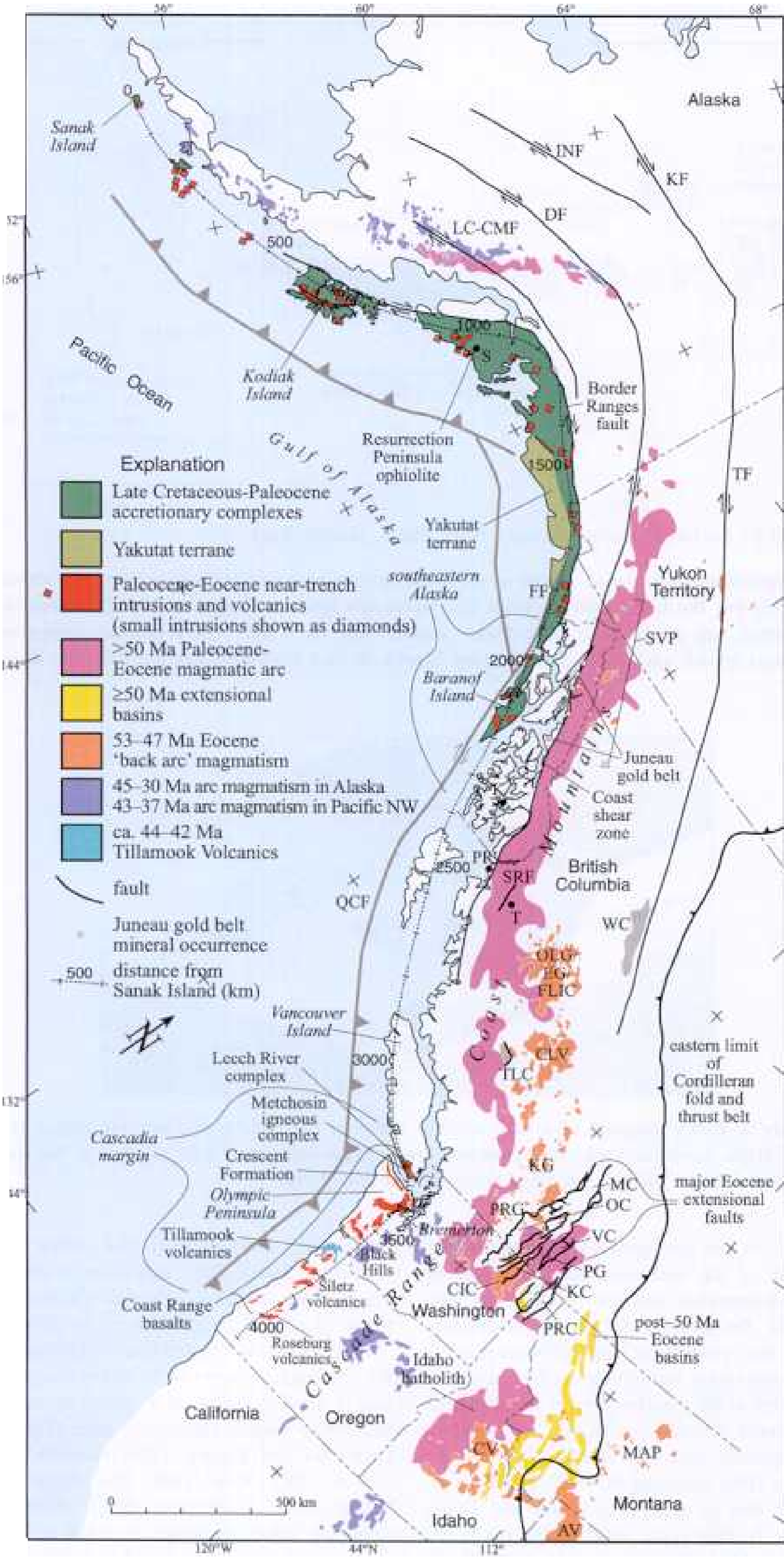
Near-trench (i.e., with respect to the present trench and modern and coeval arcs) granitic intrusions are found along the entire 2100 km length of the accretionary complex rimming south-central and southeastern Alaska (Fig. 2; Hudson et al., 1979; Bradley et al., 1993). Geochemical studies indicate that they represent anatectic melts of the host turbidites (Hudson et al., 1979) that in some areas also have a MORB (mid-oceanic-ridge basalt) component (Hill et al., 1981; Barker et al., 1992; Lytwyn et al., 2001). According to the most reliable U-Pb and $^{40}Ar/^{39}Ar$ ages, these intrusions range in age from 61 Ma in the west to 50 Ma in the east (Fig. 3; Bradley et al., 1993, 2000). Areas of high-temperature and low-pressure metamorphic rocks (Sisson et al., 1989; Sisson and Pavlis, 1993; Loney and Brew, 1987; Zumsteg et al., 2000) are coeval with the ages of nearby near-trench intrusions. Mesothermal lode-gold deposits in the accretionary complex also record an unusual thermal event. Isotopic dates of these mineral occurrences have a west-to-east trend of decreasing age and are coeval with nearby near-trench intrusions (Haeussler et al., 1995).

Ophiolitic sequences are also present in the accretionary complex. The most complete of these is on Resurrection Peninsula, near Seward, Alaska (Fig. 2). The pillow-lava section of this ophiolite (and some of the other ophiolitic sequences) has interbedded turbidite beds, which indicates that it formed in proximity to a continental margin (Helwig and Emmet, 1981). A 57 ± 1 Ma plagiogranite within the ophiolitic sequence (U-Pb zircon age, Nelson et al., 1989) was emplaced prior to the intrusion of a 53.4 ± 0.4 Ma near-trench granodiorite cutting the shear zone along which the ophiolite was emplaced ($^{40}Ar/^{39}Ar$ biotite age; Kusky and Young, 1999; Bradley et al., 2000). Thus, according to Kusky and Young (1999), less than ~3.6 m.y. elapsed between the ophiolite's birth and its incorporation into the southern Alaska accretionary complex.

The Cascadia Margin

Between southern Vancouver Island and southern Oregon, the basement rocks of the Cascadia forearc consist of ocean-crust–type basalt erupted in Paleocene and Eocene time. This basaltic basement, commonly known as the Siletz terrane or Siletzia, consists of the Metchosin Volcanics of southern Vancouver Island, the Crescent Formation of western Washington, and the Siletz River Volcanics of western Oregon (e.g., Tabor and Cady, 1978; Snavely et al., 1968). The volcanic sequence is voluminous; a 16 km thickness is exposed in the eastern Olympic Peninsula (Babcock et al., 1992), and seismic studies show that mafic crust is 20–35 km thick beneath coastal Washington and Oregon (Trehu et al., 1994; Parsons et al., 1999).

On the Olympic Peninsula, abundant pillow basalt consists of normal to en-



riched mid-oceanic-ridge basalt (MORB) and oceanic-island tholeiite (OIB); it is locally overlain by subaerial tholeiitic and alkalic basalt flows (Snavely et al., 1968; Massey, 1986; Babcock et al., 1992). Reliable isotopic age control is sparse (Fig. 3). Biostratigraphic and magnetostratigraphic ages appear more robust than available K-Ar age determinations, which are locally inconsistent with global coccolith zonation. The biostratigraphic ages indicate an age span for much of the Siletz River Volcanics in Oregon between 58.5 and 50 Ma (Bukry and Snavely, 1988; Brouwers et al., 1995; Wells et al., 1995, 2000) K-Ar and a few $^{40}Ar/^{39}Ar$ step-heating ages suggest that the basalt was erupted between 64 and 48 Ma (Duncan, 1982; Babcock et al., 1992; Pyle et al., 1997). Near Bremerton, Washington, a single U-Pb ion-microprobe age of 50.5 ± 0.6 Ma was obtained from zircons in a leucogabbro intruding, and presumably coeval with, eruptive basalt of the Crescent Formation (Haeussler et al., 2000).

Paleomagnetic studies of the Eocene pillow basalt of the Siletz terrane show that it has not

Figure 2. Late Cretaceous–Eocene tectonic elements of the Cordillera. Sources include Bradley et al. (1993), Woodsworth et al. (1992), Babcock et al. (1992), Christiansen and Yeats (1992), Moll-Stalcup et al. (1994), Parrish (1979); Parrish et al. (1988), and Morris et al. (2000). Onshore faults in black; modern offshore faults in gray. Abbreviations of faults: QCF—Queen Charlotte fault; FF—Fairweather fault; TF—Tintina fault; KF—Kaltag fault; INF—Iditarod–Nixon Fork fault; DF—Denali fault; LC-CMF—Lake Clark–Castle Mountain fault; SRF—Shames River fault. Other abbreviations: K—Ketchikan; PR—Prince Rupert; S—Seward; T—Terrace; AV—Absaroka Volcanics; CV—Challis Volcanics; MAP—Montana alkali province; CIC—Colville Igneous Complex; PG—Penticton Group volcanic rocks; PRG—Princeton Group volcanic rocks; KG—Kamloops Group volcanic rocks; CLV—Clisbako Lake volcanic rocks; OLG—Ootsa Lake Group; EG—Endako Group; FLIC—François Lake Igneous Complex; SVP—Sloko volcanic province; WC—Wolverine Complex; MC—Monashee Complex; OC—Okanogan Complex; VC—Valhalla Complex; TLC—Tatla Lake Complex. Tick marks on dotted line indicate distances in kilometers from Sanak Island keyed to distances in Figure 3.

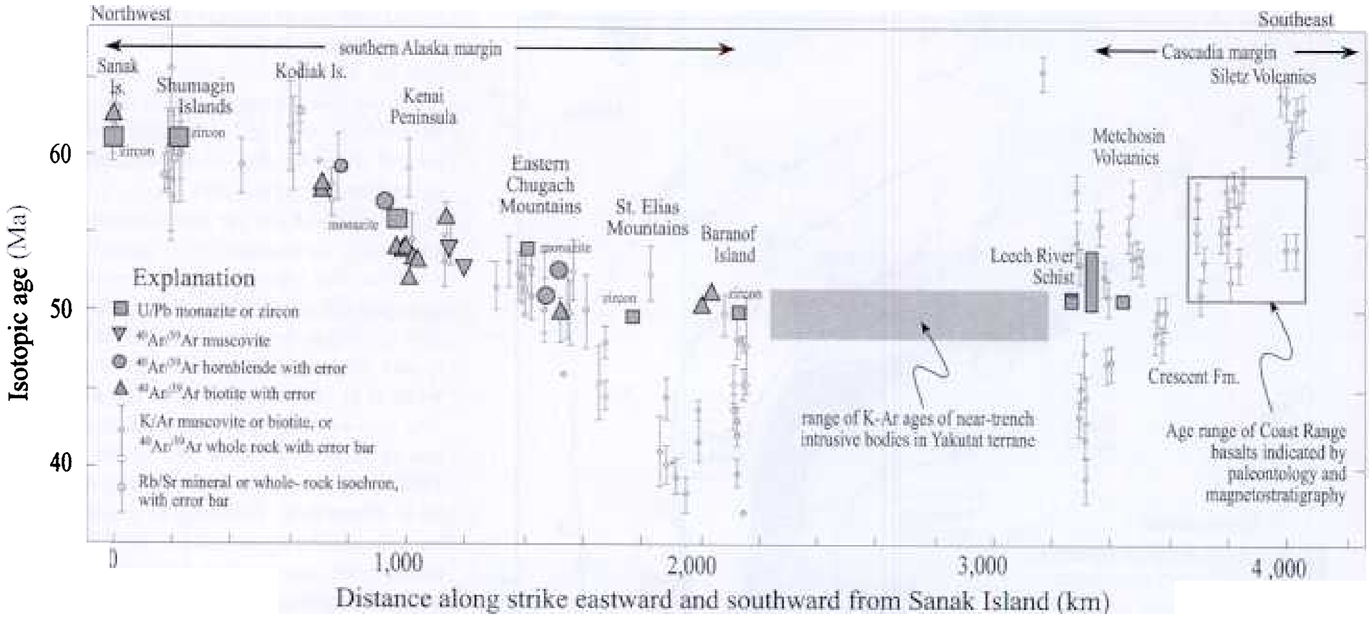


Figure 3. Plot of age vs. distance of near-trench magmatism from Sanak Island to southern Oregon along dotted line in Figure 2. Errors on analyses are smaller than the symbol size, except for the U-Pb analysis from the Metchosin Igneous Complex (Fig. 2), where the error is indicated by the vertical extent of the symbol. Age progression in southern Alaska indicates a TRT triple junction migrating west to east. Along-strike synchroneity of 50 Ma near-trench ages along southeastern Alaska–British Columbia margin indicates death of the Resurrection plate.

traveled far (Beck, 1980). However, the rocks were rotated clockwise more than 70° in middle to late Tertiary time. Because the pillow basalt is interbedded with continentally derived turbidite sequences and boulder conglomerate, it was evidently erupted on or near a continental margin (Cady, 1975; Wells et al., 2000).

The orientation of rare dike sets indicates that the Siletzia basalt was erupted where there was a component of margin-parallel extension during their emplacement. Dikes in the Siletz River Volcanics of the central Oregon coast trend northwest at present (i.e., east-northeast prior to rotation). In the unrotated Metchosin Igneous Complex and in a similar intrusive complex near Bremerton, Washington, dikes strike north-northeast (Wells et al., 1984; Massey, 1986; Beck and Engebretson, 1982; Clark, 1989; Haeussler and Clark, 2000; Fig. 2). Thus, dike orientations suggest a component of margin-parallel extension during their emplacement.

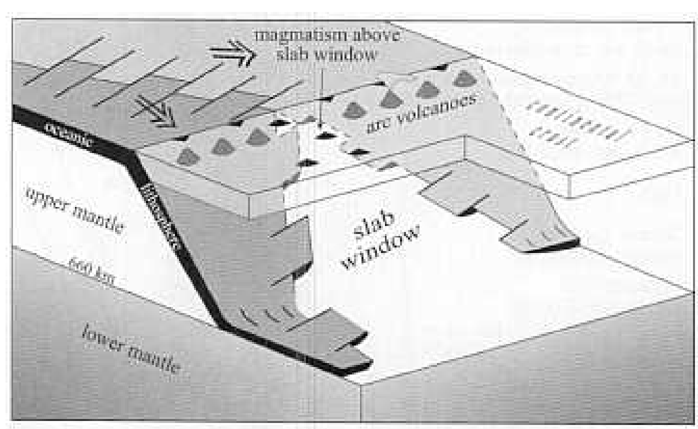


Figure 4. Block diagram of a slab window between two subducting oceanic plates at a TRT triple junction where the spreading-center segments are at a large angle to the continental margin. Slightly modified from Thorkelson (1996).

DISCUSSION

Published Interpretations of Southern Alaska and Cascadia Margin Near-Trench Magmatism

Southern Alaska

The southern Alaska age progression of near-trench magmatism over a distance of 2100 km, the geochemistry and isotopic signature of the intrusions, the accompanying high-temperature and low-pressure metamorphism, the mesothermal lode-gold deposits, and the generation and emplacement of ophiolites have been interpreted by nearly all workers as the manifestation of a ridge-trench encounter (Marshak and Karig, 1977; Helwig and Emmet, 1981; Moore et al., 1983; Plafker et al., 1994; Sisson et al., 1989; Barker et al., 1992; Bol et al., 1992; Sisson and Pavlis, 1993; Bradley et al., 1993, 2000; Pavlis and Sisson, 1995; Haeussler et al., 1995; Kusky and Young, 1999; Zumsteg et al., 2000; Lytwyn et al., 2001). This event occurred during the eastward migration of a slab window between 61 and 50 Ma (Bradley et al., 2000).

A slab window is a slab-free region beneath the convergent margin of an overriding plate and is a consequence of a spreading center interacting with a subduction zone (Fig. 4; Dickinson and Snyder, 1979; Forsythe and Nelson, 1985; Hole, 1988; Thorkelson and Taylor, 1989; Thorkelson, 1996). Where a spreading center encounters a trench (a TRT triple junction), the subducted and diverging

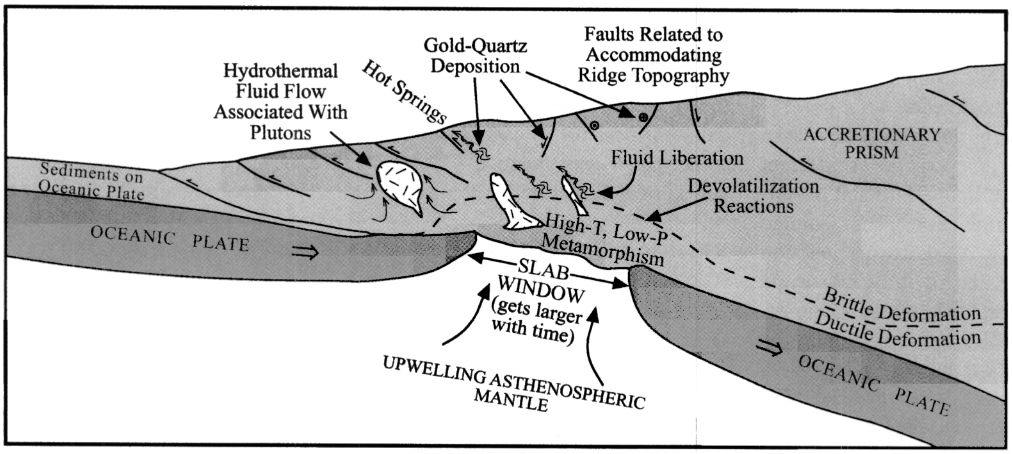


Figure 5. Interpretive cross section showing slab-window processes beneath the southern Alaska accretionary complex, from Haeussler et al. (1995). Cross section assumes ridge is at a low angle to the trench.

oceanic plates are engulfed by asthenosphere and become too hot for the slab to continue to grow, resulting in a slab window (Fig. 4). Thorkelson (1996) discussed the plate kinematics of ridge-trench intersections that produce slab windows and considered how they evolve depending on the orientation of spreading-center segments and relative plate motions. An interpretive cross section of the southern Alaska accretionary complex (Fig. 5) illustrates how the generation and emplacement of near-trench plutons, high-temperature and low-pressure metamorphism, and mesothermal lode-gold mineralization and associated faulting may be related to a migrating slab window.

An alternative hypothesis is a slab window related to slab detachment, which was favored by Hudson (1994, p. 667; 2002, personal commun.). Bergman et al. (1987) and Hudson (1994) interpreted widespread magmatism in west-central Alaska in Late Cretaceous to Paleocene time as a consequence of rapid low-angle subduction. In contrast, Paleocene–Eocene magmatism was restricted to the modern arc axis, which Hudson (1994, p. 667) attributed to

> slower convergence along a more steeply dipping subduction zone like that of today in the early Tertiary (Eocene?). This shift suggests two important early Tertiary events: (1) the cessation or slowdown of subduction (Hudson et al., 1979), and (2) a breaking and sinking of the down-going oceanic plate upon resumption of subduction. The breaking and sinking of the oceanic plate could develop a tectonic regime that would allow mantle material to be emplaced near or subjacent to the accretionary prism.

However, there is no evidence from the oceanic record for cessation or slowdown and then resumption of subduction in Paleocene–Eocene time, and much evidence to the contrary (Stock and Molnar, 1988). Moreover, modern examples of slab detachment near the toe of an accretionary wedge are nonexistent. The only documented cases of slab detachment are in a different tectonic setting (collisional orogens), at far greater depths (100–300 km), with more widespread magmatism along or behind the arc axis (e.g., Yoshioka and Wortel, 1995; Wortel and Spakman, 2000; Mahéo et al., 2002). The subduction of progressively younger oceanic crust, followed by subduction of progressively older oceanic crust after passage of a TRT triple junction might also explain the distribution of Cretaceous to Eocene magmatism and inferred subduction dip angles in south-central to west-central Alaska noted by Hudson (1994).

Cascadia Margin

Wells et al. (1984), Davis and Plafker (1986), Clark (1989), and Babcock et al. (1992) interpreted the basalt of Siletzia as the product of continental-margin rifting due to interaction with a trench-ridge-trench triple junction. Elements of this hypothesis date to Simpson and Cox (1977) who proposed that clockwise rotation of coastal Oregon was driven by subduction of the Kula-Farallon Ridge beneath the margin. Engebretson et al. (1985) noted that the simplest geometry for the Kula-Farallon-Pacific triple junction would force the Kula-Farallon Ridge to intersect the Cascadia margin. Babcock et al. (1992) suggested that MORB and OIB sequences of the Siletz terrane were erupted into marginal rift basins associated with propagation of the Kula–Farallon–North America triple junction onto the continental margin. The limited age progression (Fig. 3) of forearc magmatism suggests that the inferred triple junction did not migrate significantly. Farther east from the continental margin, Thorkelson and Taylor (1989) and Breitsprecher (2002) interpreted the geochemistry of coeval alkalic Eocene volcanic rocks in southern British Columbia as related to the Kula-Farallon slab window.

Alternatively, the Siletz terrane may represent an accreted oceanic plateau formed at the unusual setting of hotspot volcanism near both a spreading center and a continental margin (Simpson and Cox, 1977; Duncan, 1982; Wells et al., 1984, 2000). However, the lack of a clear trend in age vs. location, typical of Pacific hotspot tracks, argues against the hotspot hypothesis (Fig. 3). The Siletzia basalt represent voluminous magmatism at the continental margin linked to a Paleocene and Eocene spreading center.

Modern Slab Windows and Comparison to the Southern Alaska and Cascadia Margins

Studies of modern slab windows show that distinctive processes occur as a result of slab windows at TRT triple junctions. Studies of the Chile triple junction (e.g., Forsythe and Nelson, 1985; Forsythe et al., 1986; Rogers and Saunders, 1989; Kay et al., 1993), the Woodlark Basin triple junction in the southwestern Pacific (Taylor and Exon, 1987; Johnson et al., 1987), the Cocos-Nazca slab window beneath central America (Johnston and Thorkelson, 1997), and the slab window associated with the Mendocino triple junction (Dickinson and Snyder, 1979; Johnson and O'Neil, 1984; Donnelly-Nolan et al., 1993; Dickinson, 1997; Stanley et al., 1998) show a discrete set of features. These include high heat flow, cessation of arc volcanism, localized adakite volcanism, the presence of ophiolites, near-trench plutons, mafic to intermediate-composition volcanism in both near-trench and backarc settings, forearc hydrothermal activity and epithermal gold and silver mineralization, near-trench deformation, and underplating of the forearc.

The Cascadia margin and southern Alaska records of TRT triple junctions are as different as are the modern southern Chile and Woodlark Basin TRT triple junctions. The geologic record of the southern Alaska triple junction is broadly similar to that of the Chile triple junction, which is rapidly migrating northward. Chile has the Earth's youngest ophiolite and near-trench plutons that lie only 10–15 km from the trench (e.g., Forsythe and Nelson, 1985; Forsythe et al., 1986). In contrast, the Cascadia margin record of a possible TRT triple junction is more like the record in the Woodlark Basin. Where the Woodlark spreading ridge intersects the subduction zone, the triple junction forms a nonmigrating slab window. As a consequence, voluminous near-trench volcanism occurs. An active volcano is erupting through the downgoing oceanic plate near the trench (e.g., Taylor and Exon, 1987).

Two Coeval TRT Triple Junctions Require the Existence of the Resurrection Plate

If we accept the hypotheses that the records of near-trench magmatism in southern Alaska and the Cascadia margin are related to coeval TRT triple junctions, then an oceanic plate must have existed between them. The plate between the triple junctions lay east of the Kula plate and north of the Farallon plate (Fig. 1C). We refer to this as "the Resurrection plate," following Miller et al. (2002), after exposures near Seward, Alaska (Fig. 2), of the Resurrection Peninsula ophiolite, which may have formed at the Kula-Resurrection spreading center.

Alternative plate geometries do not satisfactorily explain the near-trench magmatic record. The Kula-Farallon slab window beneath the Pacific Northwest would explain the origin of the Siletzia basalt, but not the coeval near-trench magmatism in southern Alaska (Fig. 1A). Conversely, if the Kula–Farallon–North America triple junction is invoked to explain the southern Alaska near-trench magmatism (Fig. 1B), the origin of the Siletzia basalt of the Cascadia margin would not be explained by magmatism at a TRT triple junction. Moreover, this geometry would require an unusually high ratio of the lengths of transform offsets to ridge segments.

In order to refine and evaluate the Resurrection plate hypothesis, the remainder of this paper examines the continental-margin geology and marine magnetic record before and after the time this plate was likely destroyed. We do not discuss the birth of the Resurrection plate because we are not aware of any data that bear on its early history, but we assume that it was subducting for a significant period of time before its demise.

REGIONAL IMPLICATIONS AND RECONSTRUCTIONS

Geologic Constraints on Resurrection Plate Geometry

A paleogeographic restoration of the Cascadia to Alaska continental margin provides additional constraints on the geometry and life span of the Resurrection plate. Three factors must be considered in a reconstruction for the 60–50 Ma interval:

1. The Mesozoic and early Tertiary accretionary complex now in southern Alaska has been affected by hundreds of kilometers of right-lateral strike-slip along its backstop, the Border Ranges fault (e.g., Roeske et al., 1993; Smart et al., 1996; Appendix 1). At least some displacement occurred between 58 and 50 Ma, and the fault is pinned by a 50 Ma pluton in southeastern Alaska (Roeske et al., 1993; Haeussler et al., 1995; Johnson and Karl, 1985; L. Snee, 1996, written commun.).

2. A gap in the distribution of Mesozoic–early Tertiary accretionary complexes between southern Baranof Island and the south end of Vancouver Island (Fig. 2) suggests that these rocks were removed from this region and transported northward. The Yakutat terrane is considered to have been located in the position of the "missing" rocks and is now colliding into the cusp of southern Alaska (Fig. 2; Plafker, 1987). The eastern part of the Yakutat terrane consists of Mesozoic accretionary-complex rocks similar to those in southeastern Alaska (Plafker, 1987). Like the other accretionary complexes, they were intruded by near-trench granitic plutons. These have K-Ar dates generally between 51 and 48 Ma (Hudson et al., 1977). This relationship has resulted in a doubled-up sequence of accretionary-complex rock units on either side of the Fairweather fault (Fig. 2). The Leech River Schist of southern Vancouver Island was probably located just south of the Yakutat accretionary complex. The Leech River Schist (Fairchild and Cowan, 1982) consists of Mesozoic accretionary-complex rocks that also underwent near-trench magmatism and high-temperature, low-pressure metamorphism at ca. 51–50 Ma (Groome et al., 2000). Thus, rocks of the Mesozoic accretionary complex that show a record of near-trench magmatism formerly stretched all along the southeastern Alaska and British Columbia margin. The western part of the Yakutat terrane consists of basalt geochemically similar to basalt of Siletzia (Davis and Plafker, 1986). One of two poor-quality K-Ar dates on the Yakutat terrane basalt (50.0 ± 3.9 Ma; Plafker, 1987) lies within the range of ages for the Siletzia basalt (see Fig. 3). Siltstone conformably overlying the Yakutat terrane basalt (Plafker, 1987) has Ulatisian (late early Eocene to early middle Eocene [ca. 52–44 Ma; time scale of Berggren et al., 1995]) calcareous nannoplankton ages identical to those of interbeds in the Siletzia basalt (e.g., Wells et al., 1995; Spencer, 1984).

3. Paleomagnetic studies indicate that ~44° ± 11° of counterclockwise rotation affected all of western Alaska (Coe et al., 1985, 1989) west of the center of Prince William Sound. The rotation is inferred to have occurred in the interval between 66 and 44 Ma. Thus, the ancient continental margin was straighter than it is now, but it was still curved and had a roughly east-west orientation.

The most important aspect of these restorations is establishing that near-trench magmatism occurred at ca. 50 Ma between southern Baranof Island and southern Vancouver Island in the now-displaced Yakutat terrane part of the accretionary complex. Therefore, on a regional scale, approximately synchronous near-trench magmatism occurred at ca. 50 Ma from southeastern Alaska to the Cascadia margin (Fig. 3). The crest of the Kula-Resurrection Ridge that swept west-to-east beneath southern Alaska was thus subparallel to the southeast Alaska–Washington margin and, at ca. 50 Ma, encountered the trench almost synchronously along this entire length.

Constraints on Plate Geometry from Plate-Motion Models

Velocity triangles can be used to test whether the inferred Resurrection plate can be reconciled with known plate motions and geologic observations (Fig. 6). Although both hotspot and global plate-circuit approaches have shortcomings, the assumption that hotspots were fixed prior to ca. 43 Ma is untenable, because relative motions between the Pacific plate and adjacent plates did not change at this time and because paleomagnetic data reveal motions between the hotspots (Norton, 1995; Tarduno and Cottrell, 1997; Tarduno et al., 2001). Therefore, we use the plate-circuit–derived motions of Stock and Molnar (1988). It would be most accurate to construct velocity triangles at all three triple junctions bound-

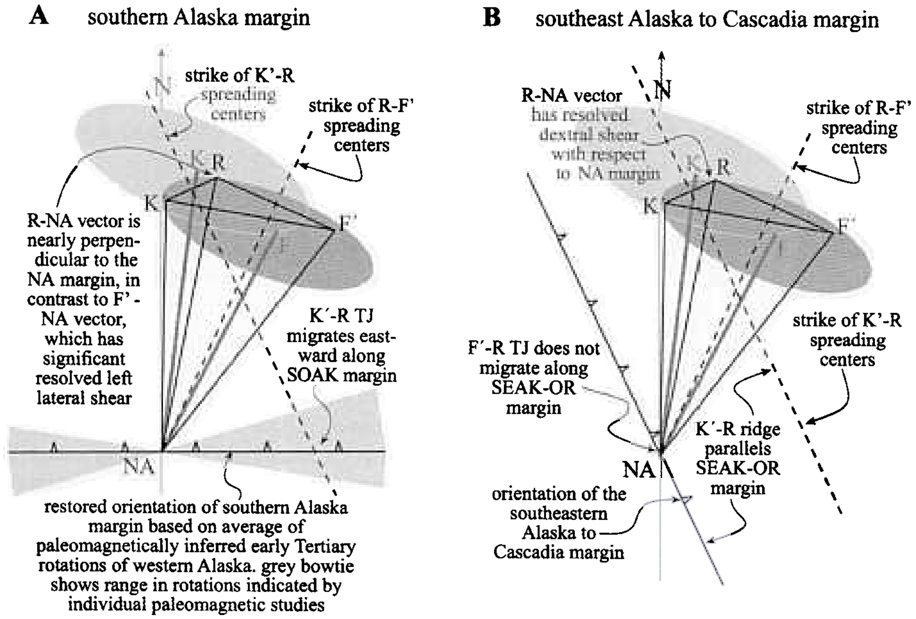


Figure 6. Velocity triangles for the Kula (K)–Farallon (F)–North American (NA) and Resurrection (R) plates. North is up. A flat Earth is assumed so that all relationships can be shown on one diagram, which is a reasonable assumption if poles of rotation are far from the plate margins. Plate-circuit–derived relative velocities and error ellipses for the interval between chrons 25n and 31r for the Kula, Farallon, and North American plates (gray lines and ovals) from near Ketchikan, Alaska, are from Stock and Molnar (1988) and Stock (2002, written commun.). Velocities at Ketchikan were used because it is near the midpoint of the convergent margin along which we infer subduction of the Resurrection plate. K′ and F′ are Kula and Farallon vectors moved within the Stock and Molnar (1988) error ellipses consistent with all constraints of the Resurrection plate hypothesis. Dashed lines are perpendicular bisectors showing orientation of spreading-center segments. (A) Diagram showing the inferred orientation of the southern Alaska margin. The orientation depicted, 270°, is the orientation of the modern margin rotated clockwise 44° in order to restore the paleomagnetically inferred rotation of western Alaska (Coe et al., 1989). (B) Diagram showing the same velocity vectors along the southeastern Alaska–Cascadia margin. Velocity vectors are identical in both A and B. For both A and B, velocities (in mm/yr) are as follows: K-NA = 116, F-NA = 102, K′-NA = 102, F′-NA = 116, R-NA = 116, K′-F′ = 71, K′-R = 23, R-F′ = 52. Azimuths are as follows: K-NA = 007°, F-NA = 027°, K′-NA = 001°, F′-NA = 038°, R-NA = 011°, K′-F′ = 280°, R-K′ = 065°, R-F′ = 294°. SOAK—southern Alaska margin; SEAK-OR—southeastern Alaska to Oregon margin.

ing the Resurrection plate, but it is simplest to view all relationships on one diagram. Therefore, we assume a flat Earth, even though absolute velocities and azimuths are slightly off. This is not a critical issue because errors in known velocity vectors are large. Also, because the poles of rotations between the known plates are generally far from the northeastern Pacific, the vectors shown are generally similar for different regions of the inferred Resurrection plate. We used Stock and Molnar's (1988) velocity vectors and error ellipses from near Ketchikan, Alaska (Fig. 6), for the interval between chrons 31r and 25n (67.7 and 56.2 Ma—calibrated with the geomagnetic polarity time scale of Cande and Kent [1995]—the youngest well-constrained interval of the Kula plate).

Geologic observations limit the family of possible velocity triangles to those that must show (1) southeastward migration of the Kula–Resurrection–North America TRT triple junction in Alaska, (2) little or no migration of the Resurrection–Farallon–North America TRT triple junction along the Cascadia margin, and (3) right-lateral shear along the southeastern Alaska–British Columbia margin, as indicated by numerous paleomagnetic and structural studies (e.g., Price and Charmichael, 1986; Smart et al., 1996; Umhoefer and Schiarizza, 1996; Cowan et al., 1997; Butler et al., 2001). In addition, the synchronous near-trench magmatism at ca. 50 Ma constrains the Kula-Resurrection Ridge to have been subparallel to the north-northwest–trending southeastern Alaska–British Columbia–Washington margin.

We show one of many possible sets of velocity triangles that satisfy all the just-described conditions within the error ellipses of the relative velocities (Fig. 6). The illustrated triangles are consistent with the following three constraints:

1. The perpendicular bisector of the K′-R vector (K′ is the Kula vector from Stock and Molnar [1988] moved within its error limits; R is Resurrection vector) represents the strike of the Kula-Resurrection Ridge, which must be parallel to the line representing the orientation of the southeastern Alaska to Cascadia margin. It is possible that the Kula-Resurrection Ridge segments did not parallel the southeastern Alaska–Cascadia margin, but rather the enveloping trend of the ridge-transform system paralleled the margin. Such a configuration would have produced fraternal slab windows (multiple coeval slab windows; Thorkelson, 1996) and increases the range in possible orientations of the R-NA vector. In Figure 6, we chose the simplest configuration where the ridge segments parallel the continental margin.

2. The intersection of the K′-R perpendicular bisector with the restored orientation of the southern Alaska margin must be east of the NA point, indicating that the K-R-NA triple junction migrated eastward across southern Alaska.

3. The perpendicular bisector of the R-F′ vector (F′ is the Farallon vector moved within its error limits) represents the orientation of the Resurrection-Farallon Ridge, and it must intersect the NA (North America) point so that the R-F-NA triple junction does not migrate significantly.

The configuration shown in Figure 6 requires that the Resurrection plate vector would have had a significant dextral-shear component along the southeastern Alaska to Oregon margin, a prediction consistent with the geologic record. These triangles also show that the Resurrection–North America velocity would have been higher than the Kula–North America velocity and that the R-NA vector trended more to the northeast. Additionally, the Kula-Resurrection Ridge would have spread more slowly than the Kula-Farallon and Farallon-Resurrection rates. Lastly, the angle between the Kula-Resurrection and

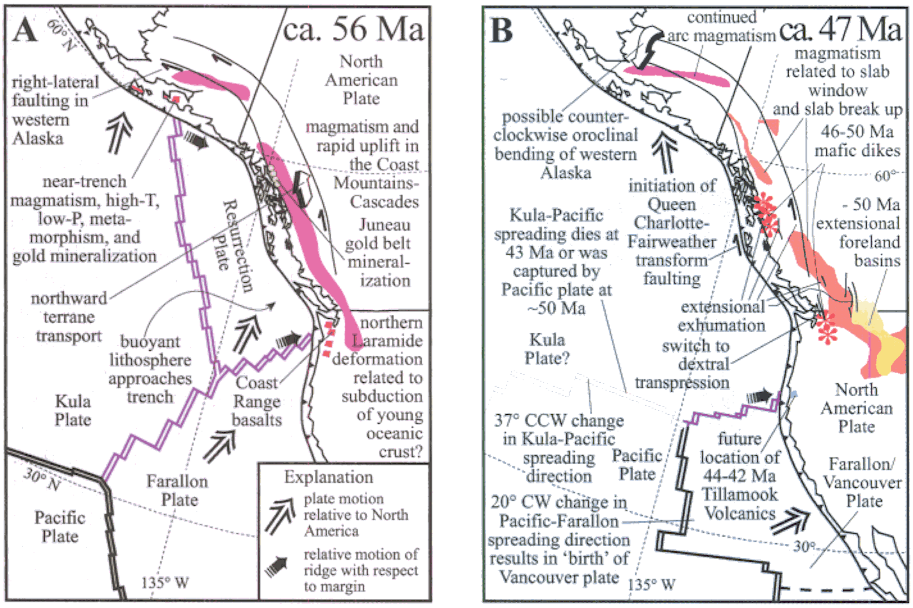


Figure 7. Cartoon showing geologic effects before and after death of the Resurrection plate. (A) About chron 25 time, ca. 56 Ma. Plate motions relative to North America and orientations of spreading-center segments from Figure 6; those in purple are unconstrained by the oceanic magnetic anomaly record. (B) About chron 21 time, or 47 Ma. Conjectural orientations of spreading-center segments unconstrained by the oceanic magnetic anomaly record are in purple. Kula-Pacific Ridge, shown in light purple, may have ceased spreading in this interval. Farallon–North America vector azimuth is from Stock and Molnar (1988); we suggest that Pacific–North America relative motion is parallel to the Queen Charlotte–Fairweather fault, which is within the error for the relative-motion azimuth (016° ± 60°) between chron 21 and chron 18 time (47 and 39 Ma) determined by Stock and Molnar (1988). "Vancouver plate" is a term used for the northern part of the Farallon plate, which is thought to have broken off from the remainder of the Farallon plate (Menard, 1978; Rosa and Molnar, 1988). See text for additional discussion.

Kula-Farallon Ridge segments would have been obtuse and larger than 120°.

Tectonic Observations Related to the Existence and Subduction of the Resurrection Plate

In our view, transitions in relative plate motions, evolution of convergent and strike-slip margins, and igneous events from Oregon to Alaska can be linked to the subduction of the Resurrection plate (Fig. 7).

Demise of the Kula and Resurrection Plates

Owing to changes in driving forces, the demise of any oceanic plate will likely modify the motions of adjacent plates. Lonsdale (1988) documented a 37° counterclockwise rotation in Kula-Pacific motions between anomaly 25n and anomaly 21n (i.e., between 55.9 and 47.9 Ma), but most of this change (21°) occurred during chron 23r (52.4–51.7 Ma). This change is synchronous with a large (20° clockwise) relative motion change between the Pacific and Farallon plates, also during chron 23r, which was related to breakup of the northern part of the Farallon plate to form the Vancouver plate (e.g., Atwater, 1989). Atwater (1989) noted that it took several million years before this change was complete (until chron 21 at 46.8 Ma). Both of these plate-motion changes were synchronous with subduction of the last of the Resurrection plate, and just predate initiation of right-transform faulting on the Queen Charlotte–Fairweather fault system (see later description of timing). Perhaps, like the Farallon plate (Atwater, 1989), the Resurrection plate fragmented near the end of its life, and thus it took some time for plate motions to readjust.

The termination of Kula-Pacific spreading may have happened in one of two ways, each having different implications with respect to the subduction death of the Resurrection plate. If part of the Kula-Pacific spreading center survived until chron 18r (40.2–40.1 Ma; Lonsdale, 1988), then a corollary of the Resurrection plate hypothesis is that after subduction of the Resurrection plate, the Kula-Farallon slab window lay beneath the Cascadia margin. This slab window provides an explanation for producing the forearc Tillamook Volcanics in central Oregon at ca. 44–42 Ma (Figs. 2, 7B; Wells et al., 1995). The Tillamook Volcanics consist of high-titanium tholeiitic to alkalic basalt and lesser dacite and rhyolite chemically similar to oceanic-island tholeiite (Wells et al., 1995). The unusual mantle-derived chemistry may be attributable to slab-window magmatism. Alternatively, Byrne (1979) and Norton (1995) favored cessation of Kula-Pacific spreading around chron 24 to chron 22 time (ca. 52.4–49.3 Ma). If so, cessation of Kula-Pacific spreading was synchronous with subduction of the Resurrection-Kula Ridge. Thus, slab pull would have ended beneath the southeastern Alaska–British Columbia–Cascadia margin, and the driving force for Kula-Pacific spreading may have ended as well. In this way, the Kula and Pacific plates may have began to move together, as plate motions changed and they began to move north parallel to the margin of British Columbia.

Subduction of the Resurrection plate at ca. 50 Ma was coincident with cessation of long-lived arc magmatism (Fig. 7) that began in middle Cretaceous time in the Coast Mountains of southern Alaska, Yukon, southeastern Alaska, British Columbia, the Cascade Range of Washington and Oregon, and the Idaho batholith (e.g., Woodsworth et al., 1992, McClelland and Mattinson, 2000; Fig. 2). A few intrusions in the northern Cascade Range are as young as 46 Ma (Babcock et al., 1985; Haugerud et al., 1988) and are perhaps related to subduction of the last piece of the Resurrection plate. Overall, from British Columbia to the Yukon Territory, no evidence exists for resumption of widespread arc magmatism along the previous axis soon after 50 Ma, a circumstance that suggests initiation of the Queen Charlotte–Fairweather transform-fault system around this time.

Tectonism of the Southeastern Alaska–British Columbia–Cascadia Margin and Western North America Interior

Subduction of the Kula-Resurrection Ridge likely led to the establishment of a transform margin from southeastern Alaska to Washington. After subduction of the Kula-Resurrection Ridge, zero-age oceanic crust would have paralleled ~2000 km of the continental margin. The positive buoyancy of this crust would have resisted subduction (Cloos, 1993). Arc magmatism stopped after 50 Ma in southeastern Alaska–British Columbia, but continued in south-central Alaska, which suggests that the surviving plate(s) (the Pacific and the Kula, if it survived to ca. 40 Ma [Lonsdale, 1988]) continued to subduct beneath the Aleutian Trench—the nearest long subduction zone (Figs. 2, 7). Structural studies in the Cascade Range demonstrate a switch from top-to-the-north shearing to right-lateral transpression at ca. 50–45 Ma (Hurlow and Nelson, 1992). This change in strain may also be related to the initiation of the transform margin.

Subduction of a spreading center parallel to a continental margin would be expected to produce geologic effects along the convergent margin prior to ridge subduction. Oceanic crust younger than 10 m.y. is buoyant with respect to the asthenosphere (Cloos, 1993), and if subducted would be expected to induce high shear stress at the base of the overriding crust. For the time near the death of the Resurrection plate, the interval just before 50 Ma is when strong coupling effects would be expected from the approaching Resurrection-Kula Ridge. Indeed the time from 60 to 50 Ma exhibits a distinctive geologic history (Fig. 7A) manifested by (1) rapid uplift and voluminous magmatism in the Coast Mountains and Cascade Range (Hollister, 1982; Crawford et al., 1987, 2000; Whitney et al., 1999; McClelland and Mattinson, 2000; Wood et al., 1991), and (2) gold mineralization in the Juneau gold belt (Goldfarb et al., 1991; Miller et al., 1994) and shortening along the Coast shear zone, the largest structure in the Coast Mountains orogen (Crawford and Crawford, 1991; McClelland et al., 1992; McClelland and Mattinson, 2000). This major orogenic episode postdates the last collisional event in the region by 30–40 m.y.

Extensional exhumation of high-grade metamorphic terranes and the development of core complexes at ca. 50 Ma in British Columbia and Washington were synchronous with the inferred subduction death of the Resurrection plate and changes in plate-margin tectonics. The greatest concentrations of core complexes lie east of the Paleocene–Eocene arc in southern British Columbia, Idaho, and western Washington State and include the Priest River and Okanogan core complexes (Fig. 2). Rapid cooling of the Priest River complex occurred between 50 and 47 Ma (Doughty and Price, 1995), and extension was ongoing at 51 Ma in the Okanogan complex. However, the Valhalla complex, which lies to the north, underwent extension and cooling earlier, mostly between 58 and 56 Ma, but continued to 52 Ma (Parrish et al., 1988). Farther north, Friedman and Armstrong (1988) found that rapid cooling of the Tatla Lake complex occurred in the interval between 53 and 46 Ma on the basis of U-Pb dating of deformed granites and Ar-Ar cooling ages on micas from the extensional shear zones. Farther north, the Wolverine Complex (Fig. 2), a 200-km-long sequence of polydeformed Hadrynian clastic rocks, also underwent cooling along its eastern margin at ca. 50–42 Ma. Although this sequence of rocks record Jurassic–Cretaceous or earlier metamorphism, the Eocene K-Ar dates indicate an important event at that time. To the west, there was extension within and along the east side of the Coast Mountains. Andronicos et al. (2000) found that a 150-km-long series of normal faults was active between 55 and 48 Ma near Prince Rupert, British Columbia. These normal faults extend northward toward Ketchikan (Fig. 2) and juxtapose high-grade kyanite- and sillimanite-bearing rocks in the core of the Coast Mountains with low-grade andalusite-bearing rocks. To the east, Heah (1991) found a major extensional shear zone along the eastern margin of the Central Gneiss Complex, near Terrace, British Columbia. Chardon and Andronicos (1997) found evidence that this structure was active between 53 and 48 Ma. In all cases except for the Valhalla complex, the extension was synchronous with, or after, the last Paleocene–Eocene arc magmatism. Therefore, the timing of the extension also marks the end of arc magmatism and the beginning of a different tectonic regime, which we infer was caused by subduction of the Resurrection plate.

In addition to the record of extension in metamorphic and plutonic rocks, the death of the Resurrection plate at 50 Ma also corresponds with the start of extensional collapse of the Cordilleran foreland fold-and-thrust belt at 49 Ma in Alberta, Montana, and Idaho (Figs. 2, 7B). Constenius (1996) documented a short interval (1–5 m.y.) between foreland thrust faulting and development of extensional half grabens. He hypothesized that this structural change was due to a large reduction in the east-west compressive stress caused by a plate-motion change. We suggest that this change can be attributed to subduction of the Kula-Resurrection spreading center and the change from subduction of buoyant oceanic crust to transform motion along the margin. Extensional collapse may have been aided by high heat flow and uplift above the slab window that opened in the wake of the sinking of the Resurrection plate.

The Resurrection plate hypothesis provides a driving mechanism for rapid northward terrane transport during right-oblique subduction prior to 50 Ma. The distance of terrane transport in western Canada and Alaska is contentious (e.g., Cowan et al., 1997), but the accepted range is from 500 to 3000 km. Agreement also exists that most northward transport was taken up west of the Tintina fault (Fig. 2) and that significant displacements predate 50 Ma (e.g., Irving and Wynne, 1991). Paleomagnetic data suggest that terrane displacements also postdate 70 Ma (e.g., Johnston et al., 1996).

The Farallon plate could not have driven northward motion of terranes because either it was not in contact with the margin of British Columbia and southeastern Alaska (Fig. 1A), or, if it was (Fig. 1B), relative motions were highly oblique to the margin. The Kula plate has often been considered the driver of northward terrane motions (e.g., Engebretson et al., 1985) because of inferred high northward relative velocities derived from the hotspot reference frame. Southward drift of the hotspots prior to 43 Ma (Norton, 1995; Tarduno and Cottrell, 1997; Tarduno et al., 2001) indicates, however, that northward velocities of the Kula plate relative to North America are smaller than generally appreciated.

In the Late Cretaceous and early Tertiary, the presence of the Resurrection plate in the northeastern Pacific is the simplest geometry in which to have a large component of right-lateral motion along the Oregon to Alaska margin at the same time as having an eastward-migrating TRT triple junction in south-central Alaska (Figs. 1, 6). The velocity of the Resurrection plate relative to North America must have been slightly higher and more toward the northeast than that of previously inferred Kula–North America motions (Fig. 6). Nonetheless, the vector was right-lateral oblique with respect to the continental margin. If southern Alaska near-trench magmatism recorded the Kula–Farallon–North America triple junction (Fig. 1B), and not the Resurrection–Kula–North America triple junction (Fig. 1C), it would be difficult to have significant northward relative motions along the British Columbia–southeastern Alaska continental margin. Alternatively, it could be argued that all displacement occurred in the interval between 70 Ma (the age of the youngest displaced rocks on which a robust paleomagnetic study has been made [Johnston et al., 1996]) and 61 Ma (the age of the oldest near-trench intrusions in southern Alaska). This timing is unlikely because $^{40}Ar/^{39}Ar$ ages on the Border Ranges fault zone (Fig. 2), one of the most important margin-parallel faults, indicate that the fault was active in a younger interval between 58 and 50 Ma (Roeske et al., 1993; Haeussler et al., 1995).

Subduction of the Resurrection plate provides the most plausible driving mechanism for right-lateral strike-slip faulting in south-central and southwestern Alaska in Late Cretaceous to Paleocene time (Fig. 7A, Miller et al., 2002). Right-lateral faults in Alaska include the Tintina, Kaltag, Iditarod–Nixon Fork, Denali-Farewell, and the Lake Clark–Castle Mountain faults (Fig. 2). At least some of these were active during the 10–20 m.y. prior to the outbreak of near-trench magmatism along the Alaskan margin (Miller et al., 2002). The Kula plate could not have come into the picture until after passage of the southern Alaska triple junction, e.g., after 61 Ma at Sanak Island. The question is whether it was flanked to the east by the Farallon plate (e.g., Bradley et al., 1993) or the Resurrection plate. It is highly unlikely that the plate to its east was the Farallon because, subject to even the maximum permissible unbending of the orocline, Farallon–North America relative motion (F-NA in Fig. 6A) along the southern Alaska margin would have had a strong left-lateral component (Fig. 6A). These same considerations do, however, permit the presence of the Resurrection plate. Both the Resurrection and Kula plate vectors would have had much smaller left-lateral components. Our estimated Resurrection–North America velocity vector (R–NA in Fig. 6) is more nearly orthogonal to the continental margin than the Farallon–North America vector and, within error, includes possible solutions with both sinistral and dextral components. Unquantifiable but large errors in Resurrection–North America relative motions and a range of possible oroclinal bends from ~29° to 54° limit this analysis. Nonetheless, the Resurrection plate is clearly the best candidate as a driver for dextral faulting in Alaska in Late Cretaceous to Paleocene time.

Western Interior Magmatism

A belt of enigmatic Eocene volcanic and plutonic rocks stretches 2500 km from Wyoming to the Yukon Territory and may be related to demise of the Resurrection plate and the opening of the Kula-Resurrection slab window. These include the Absaroka Volcanics, the Montana alkali province, the Challis Volcanics of the northwestern United States, and the Penticton, Princeton, Kamloops, Clisbako, Ootsa Lake, Endako, François Lake, and Sloko Volcanics of British Columbia and the Yukon Territory (Fig. 2; Armstrong and Ward, 1991; Morris et al., 2000; Breitsprecher, 2002). All these volcanic rocks are 300–1300 km inboard of the present continental margin and lie in a backarc position with respect to the previous arcs in the Coast Mountains, Cascade Range, and Idaho batholith (Fig. 2). The magmatic belt is ~550 km wide south of latitude 48°N, typically 200 km wide in southern British Columbia, but only 75 km wide in northern British Columbia and the Yukon (Fig. 2). Calc-alkalic affinities initially led workers to relate these rocks to subduction (e.g., Lipman et al., 1972). Trace element, rare earth element, and isotopic studies demonstrate crustal, mantle, and mixed sources (Ewing, 1980; Thorkelson, 1989; Dudás, 1991; Norman and Mertzman, 1991; Morris and Creaser, 1998; Morris et al., 2000). $^{40}Ar/^{39}Ar$ and U-Pb geochronology limits the ages of these rocks to between 53 and 45 Ma (Berger and Snee, 1992; Wooden and Box, 1996; Ispolatov et al., 1996; Janecke et al., 1997; Grainger et al., 2001; Breitsprecher, 2002). The ages show neither a north-south nor an east-west trend; they are either younger than, or coeval with, the latest stages of Paleocene–Eocene magmatism in the Coast Mountains, Cascades, and Idaho batholith (e.g., McClelland and Mattinson, 2000; Wood et al., 1991; Whitney et al., 1999; Armstrong and Ward, 1991). Metamorphic core complexes (Parrish et al., 1988; Friedman and Armstrong, 1988; Doughty and Price, 1995) and/or extensional faulting occurred synchronously with, or around the same time as, volcanism in almost all areas. In southern British Columbia, the volcanic rocks show alkalinity trends and geochemistry typical of arc volcanic sequences (Ewing, 1980; Thorkelson, 1989). However, in the northwestern United States, the magmatism may not be arc related, because alkalinity does not increase with distance from the subduction zone and because the magmatism was compositionally varied, spatially and temporally discontinuous, and coeval at different distances from the continental margin (Dudás, 1991; Norman and Mertzman, 1991; Morris et al., 2000). Moreover, Norman and Leeman (1989) demonstrated that at least some of the purported arc geochemical signature is inherited from melting of Precambrian crust. Thorkelson and Taylor (1989) first suggested that the geochemistry of volcanic rocks in southern British Columbia can be explained by a slab window, in which small amounts of partial melting of the asthenospheric mantle gave rise to the alkalic volcanic rocks. Breitsprecher (2002) also attributed the volcanic rocks in southern British Columbia to a slab window, on the basis of their distinctive geochemistry.

Two lines of evidence indicate that a temporal and spatial correlation exists between the subduction consumption of the Resurrection plate and the interior Eocene magmatism and extension (Fig. 7): (1) The Eocene magmatic rocks are found in a linear belt only beneath the continental margin where we infer that the Resurrection plate was subducted and the subsequent Kula-Resurrection slab window formed. Similar interior volcanic deposits are not found in south-central Alaska where arc volcanism has been virtually continuous. (2) Death of the Resurrection plate at ca. 50 Ma is synchronous with the middle of the age span (53–45 Ma) of the early and middle Eocene episode of volcanism and associated crustal extension. The inboard Eocene magmatic flare-up was a one-time event during the final stages of Paleocene–Eocene arc magmatism, which had been under way along coastal western North America for at least the previous 50 m.y. The interior pulse of Eocene magmatism pre- and postdates our inferred timing of Kula-Resurrection Ridge subduction, and thus some magmatism may be related to breakup and fragmentation of the Resurrection plate and some to the slab window between the Resurrection and Kula plates. For example, Breitsprecher (2002) found that the 50–49 Ma Princeton Group volcanic rocks (Fig. 2) have adakite compositions. Drummond and Defant (1990) linked adakites to partial melting of the subducted slab, and Johnston and Thorkelson (1997) found adakites associated with the modern Cocos-Nazca slab window. Thus, at least some of the Eocene volcanism may be associated with subduction of disintegrating hot young oceanic crust (Breitsprecher, 2002).

Late-Stage Magmatism

Finally, late-stage mafic magmatism in the Coast Mountains of Alaska, in British Columbia, and in the Cascade Range may be related to the Resurrection-Kula slab window. Basaltic to rhyolitic dikes intruded the Coast Mountains at ca. 50 Ma after regional deformation associated with rapid intrusion and uplift (Green et al., 1995). Lamprophyric dikes were subsequently intruded at 46 Ma (Davidson, 2001). In the Cascade Range, the widespread Teanaway mafic dike swarm (e.g., Foster, 1958), dated at ca. 48 Ma (Tabor et al., 1984), coincides with the end of arc magmatism. These mafic magmas are anomalous in the Paleocene–Eocene history of the Coast Mountains and Cascade Range. They are spatially and temporally in the correct position to be related to the Resurrection-Kula slab window. Morozov et al. (1998) found high-velocity lowermost crust interpreted as mafic underplate beneath the Coast Mountains of southernmost southeastern Alaska. The position of the mafic underplate below all other crustal rocks suggests that it may be derived from the Resurrection-Kula slab window and it might be the source region for the mafic dikes just described. In California, similar high-velocity crust is interpreted as mafic underplate associated with migration of the slab window south of the Mendocino triple junction (Stanley et al., 1998).

CONCLUSIONS

Two coeval near-trench magmatic sequences in southern coastal Alaska and along the Cascadia margin of southern British Columbia, Washington, and Oregon have previously been interpreted as the signature of TRT triple junctions. If correct, this requires the existence of a now subducted plate that occupied the northeastern Pacific in late Paleocene–early Eocene time. This inferred plate, the Resurrection plate, was located east of the Kula and north of the Farallon plates. Near-trench magmatism was synchronous from southeastern Alaska to Washington at ca. 50 Ma, and thus we infer that the crest of the Kula-Resurrection spreading center was subparallel to the continental margin and that all segments of the ridge were subducted virtually at the same time. Subduction of the Resurrection plate initiated the Queen Charlotte–Fairweather transform-fault system.

Numerous studies identify a major early Tertiary plate-motion change in the northern Pacific. Engebretson et al. (1985) put the change at ca. 56 Ma; Byrne (1979) placed it between 59 and 56 Ma; and Pavlis and Sisson (1995) put it between 56 and 52 Ma. This reorganization occurred during chron 23r time (Stock and Molnar, 1988; Lonsdale, 1988; Atwater, 1989), the age of which is 52.3–51.7 Ma, according to the most recent polarity time scale (Cande and Kent, 1995). This time was just prior to the widespread near-trench magmatic event from southeastern Alaska to Washington and may be related to subduction of the last vestiges of the Resurrection plate.

The existence and subsequent demise of the Resurrection plate provides a framework for explaining (1) northward terrane transport between 70 and 50 Ma synchronous with an eastward-migrating TRT triple junction in southern Alaska; (2) rapid uplift and voluminous magmatism in the Coast Mountains prior to 50 Ma related to subduction of buoyant oceanic crust; (3) cessation of Coast Mountains magmatism at ca. 50 Ma due to subduction of the last of the Resurrection plate; (4) mafic magmatism in the Coast Mountains and Cascades just after 50 Ma related to slab-window magmatism; (5) extensional exhumation of high-grade metamorphic terranes, development of core complexes, and extensional collapse of the Cordilleran foreland fold-and-thrust belt after 50 Ma related to initiation of the transform margin; (6) the Eocene extension and volcanism from Montana to the Yukon Territory as related to breakup of the Resurrection plate and the subsequent slab window; and (7) right-lateral margin-parallel strike-slip faulting in southern and western Alaska during Late Cretaceous and Paleocene time, which cannot be explained by Farallon convergence vectors.

APPENDIX. ARGUMENTS AGAINST LARGE PALEOMAGNETICALLY INFERRED DISPLACEMENTS

We discount paleomagnetic evidence for thousands of kilometers of northward transport of the southern Alaska accretionary complex. Two paleomagnetic studies (Plumley et al., 1983; Bol et al., 1992) indicated large-scale (25° and 13° of latitude, respectively) northward transport after the time of near-trench magmatism. Both of the paleomagnetic studies are excellent in their scope and presentation of paleomagnetic results. However, aspects of the structural geology, paleomagnetism, and rock magnetism of these studies allow that a primary remanence may not have been preserved and that displacements are not as large as they concluded. The study of the Resurrection Peninsula ophiolite by Bol et al. (1992) had to use a two-stage unfolding of sheeted-dike and bedding orientations for the data to pass a fold test. Moreover, as much as ~3.6 m.y. elapsed between formation of the ophiolite and its emplacement into the accretionary complex (Kusky and Young, 1999). Therefore, because the ophiolite was not a part of the accretionary complex when it formed, the paleolatitude, if correct, would not necessarily reflect the paleolatitude of the accretionary complex. Regarding the Plumley et al. (1983) Kodiak Island study, one of two sampling areas had a highly unusual 60° plunging fold, and they also used a logical, though necessarily arbitrary, two-stage unfolding process when tilt-correcting the data. Moreover, the rocks have low-Ti titanomagnetites, which have Curie temperatures below 508 °C, and thus have a correspondingly less stable remanence. In addition, the Kodiak Island samples were collected from two localities 80 km apart, each of which yielded significantly different inclinations and declinations that were averaged together for the final result.

We suspect the "primary" remanence in both studies may be a prefolding secondary magnetization. In the Franciscan Complex of California, large-scale displacements were inferred from prefolding remagnetizations acquired at the time the rocks were dipping toward the trench (Hagstrum and Sedlock, 1991). In this manner, remnant magnetizations are shallow, pass a fold test, and appear to be primary, but they are not. The in situ secondary components of magnetization in the Kodiak study (Plumley et al., 1983) are either concordant with the expected direction for North America or steeper, which indicates that the rocks were tilted to the southeast after being remagnetized. This relationship is consistent with a remagnetization hypothesis.

ACKNOWLEDGMENTS

Reviews by Alison Till and Jon Hagstrum were greatly appreciated. Joann Stock rummaged through numerous old files to provide K-F-NA velocities used in Figure 6, but the use of the those numbers and interpretations are entirely ours. Discussions with Dave Chapman, Cam Davidson, Rich Friedman, Sue Karl, Scott Paterson, Dave Rowley, and Derek Thorkelson were also valuable. Journal reviews by Derek Thorkelson and Dave Scholl substantially improved the manuscript, as did comments by associate editor Basil Tikoff.

REFERENCES CITED

Andronicos, C.L., Rusmore, M.E., Chardon, D.H., Hollister, L.S., Davidson, C., and Woodsworth, G.J., 2000, Eocene crustal extension within the Coast plutonic complex, British Columbia: Geological Society of America Abstracts with Programs, v. 32, no. 6, p. 2.

Armstrong, R.L., and Ward, P.L., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: The temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, v. 97, p. 6799–6821.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536.

Atwater, T., 1989, Plate tectonic history of the northeast Pacific and western North America, *in* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The eastern Pacific Ocean and Hawaii: Boulder, Colorado, Geological Society of America, Geology of North America, v. N, p. 21–72.

Babcock, R.S., Armstrong, R.L., and Misch, P., 1985, Isotopic constraints on the age and origin of the Skagit Metamorphic Suite and related rocks: Geological Society of America Abstracts with Programs, v. 17, p. 339.

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 northern Coast Range volcanic province, Washington and British Columbia: Journal of Geophysical Research, v. 97, p. 6799–6821.

Barker, F., Farmer, G.L., Ayuso, R.A., Plafker, G., and Lull, J.S., 1992, The 50 Ma granodiorite of the eastern Gulf of Alaska: Melting in an accretionary prism in the forearc: Journal of Geophysical Research, v. 97, p. 6757–6778.

Beck, M.E., Jr., 1980, Paleomagnetic record of plate-margin tectonic processes along the western edge of North America: Journal of Geophysical Research, v. 85, p. 7115–7131.

Beck, M.E., Jr., and Engebretson, D.C., 1982, Paleomagnetism of small basalt exposures in the west Puget Sound area, Washington, and speculations on the accretionary origin of the Olympic Mountains: Journal of Geophysical Research, v. 87, p. 3755–3760.

Berger, B.R., and Snee, L.W., 1992, Thermochronologic constraints on mylonite and detachment fault development, Kettle Highlands, northeastern Washington and southern British Columbia: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. 65.

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.P., 1995, A revised Cenozoic geochronology and chronostratigraphy, *in* Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, J., eds., Geochronology, time scales and global stratigraphic correlation: SEPM (Society for Sedimentary Geology) Special Publication 54, p. 129–212.

Bergman, S.C., Hudson, T.L., and Doherty, D.J., 1987, Magmatic rock evidence for a Paleocene change in

the tectonic setting of Alaska: Geological Society of America Abstracts with Programs, v. 19, p. 586–587.
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. 17,213–17,232.
Bradley, D.C., Haeussler, P., and Kusky, T.M., 1993, Timing of early Tertiary ridge subduction in southern Alaska: U.S. Geological Survey Bulletin 2068, p. 163–177.
Bradley, D.C., Parrish, R., Clendenen, W., Lux, D., Layer, P., Heizler, M., and Donley, D.T., 2000, New geochronological evidence for the timing of early Tertiary ridge subduction in southern Alaska: U.S. Geological Survey Professional Paper 1615, p. 5–21.
Breitsprecher, K., 2002, Volcanic stratigraphy, petrology and tectonic setting: Eastern margin of the Eocene Kamloops Group, south-central British Columbia [M.S. thesis]: Burnaby, British Columbia, Simon Fraser University, 221 p., 1 plate, scale 1:50,000.
Brouwers, E., Bukry, D., Marincovich, L., Jr., and In-Chang, R., 1995, Paleoecology, biostratigraphy, and depositional history of Paleocene to middle Eocene rocks of the Tyee basin, western Oregon: American Association of Petroleum Geologists Bulletin, v. 79, no. 4, p. 580.
Bukry, D., and Snavely, P.D., Jr., 1988, Coccolith zonation for Paleogene strata in the Oregon Coast Range, *in* Filewicz, M.V., and Squires, R.L., eds., Paleogene stratigraphy, west coast of North America: Pacific Section, Society of Economic Paleontologists and Mineralogists, West Coast Paleogene Symposium, v. 58, p. 251–263.
Butler, R.F., Gehrels, G.E., and Kodama, K.P., 2001, A moderate translation alternative to the Baja British Columbia hypothesis: GSA Today, v. 11, no. 6, p. 4–9.
Byrne, T., 1979, Late Paleocene demise of the Kula-Pacific spreading center: Geology, v. 7, p. 341–344.
Cady, W.M., 1975, Tectonic setting of the Tertiary volcanic rocks of the Olympic Peninsula, Washington: U.S. Geological Survey Journal of Research, v. 3, p. 573–582.
Cande, S.C., and Kent, D.V., 1995, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 100, p. 6093–6095.
Chardon, D.H., and Andronicos, C.L., 1997, The Central gneiss complex: An asymmetrical extensional gneiss dome bounded by the Coast shear zone: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 84.
Christiansen, R.L., Yeats, R.S., Graham, S.A., Níem, W.A., Niem, A.R., Snavely, P.D., Jr., 1992, Post-Laramide geology of the U.S. Cordilleran region, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S., Decade of North American Geology Project Series: Boulder, Colorado, Geological Society of America, p. 261–406.
Clark, K.P., 1989, The stratigraphy and geochemistry of the Crescent Formation basalts and the bedrock geology of associated igneous rocks near Bremerton, Washington [M.S. thesis]: Bellingham, Western Washington University, 171 p.
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, p. 715–737.
Coe, R.S., Globerman, B.R., Plumley, P.W., and Thrupp, G., 1985, Paleomagnetic results from Alaska and their tectonic implications, *in* Howell, D.G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 1, p. 85–108.
Coe, R.S., Globerman, B.R., and Thrupp, G.A., 1989, Rotation of central and southern Alaska in the early Tertiary: Oroclinal bending by megakinking?, *in* Kissel, C., and Laj, C., eds., Paleomagnetic rotations and continental deformation: New York, Kluwer, p. 327–342.
Constenius, K.N., 1996, Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt: Geological Society of America Bulletin, v. 108, p. 20–39.
Cowan, D.S., Brandon, M.T., and Garver, J.I., 1997, Geologic tests of hypotheses for large coastwise displacements—A critique illustrated by the Baja British Columbia controversy: American Journal of Science, v. 297, p. 117–173.
Crawford, M.L., and Crawford, W.A., 1991, Magma emplacement in a convergent tectonic orogen, southern Revillagigedo Island, southeastern Alaska: Canadian Journal of Earth Sciences, v. 28, p. 929–938.
Crawford, M.L., Hollister, L.S., and Woodsworth, G.J., 1987, Crustal deformation and regional metamorphism across a terrane boundary, Coast Plutonic Complex, British Columbia: Tectonics, v. 6, p. 343–361.
Crawford, M.L., Crawford, W.A., and Gehrels, G.E., 2000, Terrane assembly and structural relationships in the eastern Prince Rupert quadrangle, British Columbia, *in* Stowell, H.H., and McClelland, W.C., eds., Tectonics of the Coast Mountains, southern Alaska and British Columbia: Boulder, Geological Society of America Special Paper 343, p. 1–21.
Davidson, C., 2001, Timing and style of deformation across the Coast steep zone, Prince Rupert, British Columbia: Eos (Transactions, American Geophysical Union), v. 82, Abstract S22D–06, p. F857.
Davis, A.S., and Plafker, G., 1986, Eocene basalts from the Yakutat terrane: Evidence for the origin of an accreting terrane in southern Alaska: Geology, v. 14, p. 963–966.
Dickinson, W.R., 1997, Tectonic implications of Cenozoic volcanism in coastal California: Geological Society of America Bulletin, v. 109, p. 936–954.
Dickinson, W.R., and Snyder, W.S., 1979, Geometry of subducted slabs related to San Andreas transform: Journal of Geology, v. 87, p. 609–627.
Donnelly-Nolan, J.M., Burns, M.G., Goff, F.E., Peters, D.K., and Thompson, J.M., 1993, The Geysers–Clear Lake area, CA: Thermal waters, mineralization, volcanism, and geothermal potential: Economic Geology, v. 88, p. 301–316.
Doughty, T.P., and Price, R.A., 1995, Tectonic evolution of the Priest River complex, northern Idaho and Washington: A reappraisal of the Newport fault with new insights on metamorphic core complex formation: Tectonics, v. 18, p. 375–393.
Drummond, M.S., and Defant, M.J., 1990, A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting; Archean to modern comparisons: Journal of Geophysical Research, v. 95, p. 21,503–21,521.
Dudás, F.Ö., 1991, Geochemistry of igneous rocks from the Crazy Mountains, Montana, and tectonic models for the Montana alkali province: Journal of Geophysical Research, v. 96, p. 13,261–13,277.
Duncan, R.A., 1982, A captured island chain in the Coast Range of Oregon and Washington: Journal of Geophysical Research, v. 87, p. 10,827–10,837.
Engebretson, D.C., Cox, A.V., and Gordon, R.G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, 59 p.
Ewing, T.E., 1980, Paleogene tectonic evolution of the Pacific Northwest: Journal of Geology, v. 88, p. 619–639.
Fairchild, L.H., and Cowan, D.S., 1982, Structure, petrology and tectonic history of the Leech River Complex northwest of Victoria, Vancouver Island: Canadian Journal of Earth Sciences, v. 19, p. 1817–1835.
Forsythe, R., and Nelson, E., 1985, Geological manifestations of ridge collision: Evidence from the Golfo de Penas–Taitao basin, southern Chile: Tectonics, v. 4, p. 477–495.
Forsythe, R., Nelson, E.P., Carr, M.J., Kaeding, M.E., Herve, M., Mpodozis, C., Soffia, J.M., and Harambour, S., 1986, Pliocene near-trench magmatism in southern Chile: A possible manifestation of ridge collision: Geology, v. 14, p. 23–27.
Foster, R.J., 1958, The Teanaway dike swarm of central Washington: American Journal of Science, v. 256, p. 644–653.
Friedman, R.M., and Armstrong, R.L., 1988, Tatla Lake metamorphic complex: An Eocene metamorphic core complex on the southwestern edge of the Intermontane belt of British Columbia: Tectonics, v. 7, p. 1141–1166.
Goldfarb, R.J., Snee, L.W., Miller, L.D., and Newberry, R.J., 1991, Rapid dewatering of the crust deduced from ages of mesothermal gold deposits: Nature, v. 354, p. 296–298.
Grainger, N.C., Villeneuver, M.E., Heaman, L.M., and Anderson, R.G., 2001, New U-Pb and Ar/Ar isotopic age constraints on the timing of Eocene magmatism, Fort Fraser and Nechako River map areas, central British Columbia: Canadian Journal of Earth Sciences, v. 38, p. 679–696.
Green, D., Greig, J.C., and Friedman, R.M., 1995, Geological setting, geochronology, and thermal modeling of the Portland Canal dyke swarm, Stewart area, northwestern British Columbia: Geological Survey of Canada, Current Research 1995-E, p. 47–57.
Groome, W.G., Thorkelson, D.J., Friedman, R.M., Massey, N.W.D., and Marshall, D.D., 2000, Eocene magmatism in the Leech River Complex: Evidence for spreading ridge subduction and slab window formation: Geological Society of America Abstracts with Programs, v. 32, no. 1, p. A-15.
Grow, J.A., and Atwater, T., 1970, Mid-Tertiary tectonic transition in the Aleutian arc: Geological Society of America Bulletin, v. 81, p. 3715–3722.
Haeussler, P.J., and Clark, K.M., 2000, Geologic map of the Wildcat Lake 7.5′ quadrangle, Kitsap County, Washington: U.S. Geological Survey Open-File Report 00–356, scale 1:24,000, 1 sheet: http://geopubs.wr.usgs.gov/open-file/of00–356/.
Haeussler, P.J., Bradley, D., Goldfarb, R., and Snee, L., 1995, Link between ridge subduction and gold mineralization in southern Alaska: Geology, v. 23, p. 995–998.
Haeussler, P.J., Wells, R.E., Blakely, R.J., Murphy, J., and Wooden, J.L., 2000, Structure and timing of movement on the Seattle fault at Green and Gold Mountains, Kitsap Peninsula, Washington: Geological Society of America Abstracts with Programs, v. 32, no. 6, p. A-16.
Hagstrum, J.T., and Sedlock, R.L., 1991, Remagnetization and northward translation of Mesozoic red chert from Cedros Island and the San Benito Islands, Baja California, Mexico, Reply: Geological Society of America Bulletin, v. 103, p. 968–969.
Haugerud, R.A., Tabor, R.W., Stacey, J., and Van der Hayden, P., 1988, What is in the core of the North Cascades, Washington? A new look at the structure and metamorphic history of the Skagit Gneiss of Misch (1966): Geological Society of America Abstracts with Programs, v. 20, p. 168.
Heah, T.S.T., 1991, Mesozoic ductile shear and Paleogene extension along the eastern margin of the Central Gneiss Complex, coast belt, Shames River area, near Terrace, British Columbia [M.S. thesis]: Vancouver, University of British Columbia, 52 p.
Helwig, J., and Emmet, P., 1981, Structure of the early Tertiary Orca Group in Prince William Sound and some implications for the plate tectonic history of southern Alaska: Journal of the Alaska Geological Society, v. 1, p. 12–35.
Hill, M.D., Morris, J., and Whelan, J., 1981, Hybrid granodiorites intruding the accretionary prism, Kodiak, Shumagin, and Sanak Islands, southwest Alaska: Journal of Geophysical Research, v. 86, p. 10,569–10,590.
Hole, M.J., 1988, Post-subduction alkaline volcanism along the Antarctic Peninsula: Geological Society [London] Journal, v. 145, p. 985–998.
Hollister, L.S., 1982, Metamorphic evidence for rapid (2 mm/yr) uplift of a part of the Central Gneiss Complex, Coast Mountains, B.C.: Canadian Mineralogist, v. 20, p. 319–332.
Hudson, T.L., 1994, Crustal melting events in Alaska, *in* Plafker, G., and Berg, H.C., eds., The geology of Alaska: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-1, p. 657–670.

Hudson, T., Plafker, G., and Lanphere, M.A., 1977, Intrusive rocks of the Yakutat–St. Elias area, south-central Alaska: U.S. Geological Survey Journal of Research, v. 5, p. 155–172.

Hudson, T., Plafker, G., and Peterman, Z.E., 1979, Paleogene anatexis along the Gulf of Alaska margin: Geology, v. 7, p. 573–577.

Hurlow, H.A., and Nelson, B.K., 1992, U-Pb zircon and monazite ages for the Okanogan Range batholith, Washington: Implications for the magmatic and tectonic evolution of the southern Canadian and northern United States Cordillera: Geological Society of America Bulletin, v. 105, p. 231–240.

Irving, E., and Wynne, P.J., 1991, Paleomagnetic evidence for motions of parts of the Canadian Cordillera: Tectonophysics, v. 187, p. 259–275.

Ispolatov, V.O., Dudas, F.O., Snee, L.W., and Harlan, S.S., 1996, Precise dating of the Lowland Creek Volcanics, west-central Montana: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. 484.

Janecke, S.U., Hammond, B.F., Snee, L.W., and Geissman, J.W., 1997, Rapid extension in an Eocene volcanic arc: Structure and paleogeography of an intra-arc half graben in central Idaho: Geological Society of America Bulletin, v. 109, no. 3, p. 253–267.

Johnson, B.R., and Karl, S.M., 1985, Geologic map of western Chichagof and Yakobi Islands, southeastern Alaska: U.S. Geological Survey Miscellaneous Investigations Map I-1506, scale 1:125,000, 1 sheet, 15 p.

Johnson, C.M., and O'Neil, J.R., 1984, Triple junction magmatism: A geochemical study of Neogene volcanic rocks in western California: Earth and Planetary Science Letters, v. 71, p. 241–262.

Johnson, R.W., Jaques, A.L., Langmuir, C.H., Perfit, M.R., Staudigel, H., Dunkley, P.N., Chappell, B.W., Taylor, S.R., Baekisapa, M., 1987, Ridge subduction and forearc volcanism; petrology and geochemistry of rocks dredged from the western Solomon Arc and Woodlark Basin, *in* Taylor, B., and Exon, N.F., eds., Marine geology, geophysics, and geochemistry of the Woodlark Basin-Solomon Islands, Circum-Pacific Council for Energy and Mineral Resources Earth Sciences Series: Houston, Circum-Pacific Council for Energy and Mineral Resources, v. 7, p. 155–226.

Johnston, S.T., and Thorkelson, D.J., 1997, Cocos-Nazca slab window beneath Central America: Earth and Planetary Science Letters, v. 146, p. 465–474.

Johnston, S.T., Wynne, P.J., Francis, D., Hart, C.J.R., Enkin, R.J., and Engebretson, D.C., 1996, Yellowstone in Yukon: The Late Cretaceous Carmacks Group: Geology, v. 24, p. 997–1000.

Kay, S.M., Ramos, V.A., and Marquez, M., 1993, Evidence in Cerro Pampa volcanic rocks for slab-melting prior to ridge-trench collision in southern South America: Journal of Geology, v. 101, p. 703–714.

Kusky, T.M., and Young, C.M., 1999, Emplacement of the Resurrection Peninsula ophiolite in the southern Alaska forearc during a ridge-trench encounter: Journal of Geophysical Research, v. 104, p. 29,025–29,054.

Lipman, P.W., Prostka, H.J., Christiansen, R.L., 1972, Cenozoic volcanism and plate-tectonic evolutionof the western United States; I, Early and middle Cenozoic; Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences, v. 271, p. 217–248.

Loney, R.A., and Brew, D.A., 1987, Regional thermal metamorphism and deformation of the Sitka Graywacke, southern Baranof Island, southeastern Alaska: U.S. Geological Survey Bulletin 1779, 17 p.

Lonsdale, P., 1988, Paleogene history of the Kula plate: Geological Society of America Bulletin, v. 100, p. 733–754.

Lytwyn, J., Lockhart, S., Casey, J., and Kusky, T., 2001, Geochemistry of near-trench intrusives associated with ridge subduction, Seldovia Quadrangle, southern Alaska: Journal of Geophysical Research, v. 105, p. 27,957–27,978.

Mahéo, G., Guillot, S., Blichert-Toft, J., Rolland, Y., and Pêcher, A., 2002, A slab breakoff model for the Neogene thermal evolution of South Karakorum and South Tibet: Earth and Planetary Science Letters, v. 195, p. 45–58.

Marshak, R.S., and Karig, D.E., 1977, Triple junctions as a cause for anomalously near-trench igneous activity between the trench and volcanic arc: Geology, v. 5, p. 233–236.

Massey, N.W.D., 1986, Metchosin Igneous Complex, southern Vancouver Island: Ophiolite stratigraphy developed in an emergent island setting: Geology, v. 14, p. 602–605.

McClelland, W.C., and Mattinson, J.M., 2000, Cretaceous–Tertiary evolution of the western Coast Mountains, central southeastern Alaska, *in* Stowell, H.H., and McClelland, W.C., eds., Tectonics of the Coast Mountains, southern Alaska and British Columbia: Geological Society of America Special Paper 343, p. 159–182.

McClelland, W.C., Gehrels, G.E., Samson, S.D., and Patchett, P.J., 1992, Structural and geochronologic relations along the western flank of the Coast Mountains batholith: Stikine River to Cape Fanshaw, central southeastern Alaska: Journal of Structural Geology, v. 14, p. 475–489.

Menard, H.W., 1978, Fragmentation of the Farallon plate by pivoting subduction: Journal of Geology, v. 86, p. 99–110.

Miller, L.D., Goldfarb, R.J., Gehrels, G.E., and Snee, L.W., 1994, Genetic links between fluid cycling, vein formation, regional deformation, and plutonism in the Juneau gold belt, southeastern Alaska: Geology, v. 22, p. 203–206.

Miller, M.L., Bradley, D.C., Bundtzen, T.K., and McClelland, W., 2002, Late Cretaceous through Cenozoic strike-slip tectonics of southwestern Alaska: Journal of Geology, v. 110, p. 247–270.

Moll-Stalcup, E.J., Brew, D.A., and Vallier, T.L., 1994, Latest Cretaceous and Cenozoic magmatic rocks of Alaska, *in* Plafker, G., and Berg, H.C., eds., The geology of Alaska: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-1, 1 sheet, scale 1:2,500,000.

Moore, J.C., Byrne, T., Plumley, P.W., Reid, M., Gibbons, H., and Coe, R.S., 1983, Paleogene evolution of the Kodiak Islands, Alaska: Consequences of ridge-trench interaction in a more southerly latitude: Tectonics, v. 2, p. 265–293.

Morozov, I.B., Smithson, S.B., Hollister, L.S., and Diebold, J.B., 1998, Wide-angle seismic imaging across accreted terranes, southeastern Alaska and western British Columbia: Tectonophysics, v. 299, p. 281–296.

Morris, G.A., and Creaser, R.A., 1998, The petrogenesis of the Mount Skukum/Bennett Lake Igneous Complex, Yukon Territory, and reflections on the Eocene tectonics of the Canadian Cordillera, *in* Cook, F., and Erdmer, P., compilers, Slave–Northern Cordillera Lithospheric Evolution (SNORCLE) Transect and Cordilleran Tectonics Workshop Meeting (March 6–8), Simon Fraser University: Lithoprobe Report 64, p. 165–170.

Morris, G.A., Larson, P.B., and Hooper, P.R., 2000, "Subduction style" magmatism in a non-subduction setting: The Colville Igneous Complex, NE Washington State, USA: Journal of Petrology, v. 41, p. 43–67.

Nelson, S.W., Miller, M.L., and Dumoulin, J.A., 1989, Resurrection Peninsula ophiolite, *in* Nelson, S.W., and Hamilton, T.W., eds., Guide to the geology of Resurrection Bay, eastern Kenai Fiords area, Alaska: Anchorage, Geological Society of Alaska, p. 10–20.

Norman, M.D., and Leeman, W.P., 1989, Geochemical evolution of Cenozoic–Cretaceous magmatism and its relation to tectonic setting, southwestern Idaho, U.S.A.: Earth and Planetary Science Letters, v. 94, p. 78–96.

Norman, M.D., and Mertzman, S.A., 1991, Petrogenesis of Challis Volcanics from central and southwestern Idaho: Trace element and Pb isotopic evidence: Journal of Geophysical Research, v. 96B, p. 13,279–13,293.

Norton, I.O., 1995, Plate motions in the North Pacific: The 43 Ma nonevent: Tectonics, v. 14, p. 1080–1094.

Parrish, R.R., 1979, Geochronology and tectonics of the northern Wolverine Complex, British Columbia: Canadian Journal of Earth Sciences, v. 16, p. 1428–1438.

Parrish, R.R., Carr, S.D., and Parkinson, D.L., 1988, Eocene extensional tectonics and geochronology of the southern Omineca belt, British Columbia and Washington: Tectonics, v. 7, p. 181–212.

Parsons, T., Wells, R.E., Fisher, M.A., Flueh, E., and ten Brink, U.S., 1999, Three-dimensional velocity structure of Siletzia and other accreted terranes in the Cascadia forearc of Washington: Journal of Geophysical Research, v. 104, p. 18,015–18,039.

Pavlis, T.L., and Sisson, V.B., 1995, Structural history of the Chugach metamorphic complex in the Tana River region, eastern Alaska: A record of Eocene ridge subduction: Geological Society of America Bulletin, v. 107, p. 1333–1355.

Plafker, G., 1987, Regional geology and petroleum potential of the northern Gulf of Alaska continental margin, *in* Scholl, D.W., Grantz, A., and Vedder, J.G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins—Beaufort Sea to Baja California: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 229–268.

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, Geological Society of America, Geology of North America, v. G-1, p. 389–449.

Plumley, P.W., Coe, R.S., and Byrne, T., 1983, Paleomagnetism of the Paleocene Ghost Rocks Formation, Prince William terrane, Alaska: Tectonics, v. 2, p. 295–314.

Price, R.A., and Charmichael, D.M., 1986, Geometric test for Late Cretaceous–Paleocene intracontinental transform faulting in the Canadian Cordillera: Geology, v. 14, p. 468–471.

Pyle, D.G., Hanan, B.B., Graham, D.W., and Duncan, R.A., 1997, Siletzia: Geochemistry and geochronology of Yellowstone hot spot volcanism in a suboceanic setting: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. 298.

Roeske, S.M., Snee, L.W., and Bunds, M.P., 1993, $^{40}Ar/^{39}Ar$ dates from the Border Ranges fault system, a hydrothermally altered brittle-ductile transition strike-slip shear zone, southern Alaska: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. A419.

Rogers, G., and Saunders, A.D., 1989, Magnesian andesites from Mexico, Chile and the Aleutian Islands: Implications for magmatism associated with ridge-trench collisions, *in* Crawford, A.J., ed., Boninites and related rocks: London, Unwin Hyman, p. 416–445.

Rosa, J.W.C., and Molnar, P., 1988, Uncertainties in reconstructions of the Pacific, Farallon, Vancouver, and Kula plates and constraints on the rigidity of the Pacific and Farallon (and Vancouver) plates between 72 and 34 Ma: Journal of Geophysical Research, v. 89, p. 6980–6994.

Simpson, R.W., and Cox, A., 1977, Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range: Geology, v. 5, p. 585–589.

Sisson, V.B., and Pavlis, T.L., 1993, Geologic consequences of plate reorganization: An example from the Eocene southern Alaska forearc: Geology, v. 21, p. 913–916.

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.

Smart, K.J., Pavlis, T.L., Sisson, V.B., Roeske, S.M., and Snee, L.W., 1996, The Border Ranges fault system in Glacier Bay National Park, Alaska: Evidence for major early Cenozoic dextral strike-slip motion: Canadian Journal of Earth Sciences, v. 33, p. 1268–1282.

Snavely, P.D., Jr., MacLeod, N.S., and Wagner, H.C., 1968, Tholeiitic and alkalic basalts of the Eocene Siletz River Volcanics, Oregon Coast Range: American Journal of Science, v. 266, p. 454–481.

Spencer, P.K., 1984, Lower Tertiary biostratigraphy and paleoecology of the Quilcene–Discovery Bay area, northeast Olympic Peninsula, Washington [Ph.D. thesis]: Seattle, University of Washington, 173 p.

Stanley, W.D., Benz, H.M., Walters, M.A., Villasenor, A., and Rodriguez, B.D., 1998, Tectonic controls on magmatism in The Geysers–Clear Lake region: Evidence from new geophysical models: Geological Society of America Bulletin, v. 110, p. 1193–1207.

Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary positions of North America relative to the Farallon, Kula, and Pacific plates: Tectonics, v. 7, p. 1339–1384.

Tabor, R.W., and Cady, W.M., 1978, Geologic map of the Olympic Peninsula: U.S. Geological Survey Miscellaneous Investigations Map I-994, scale 1:125,000.

Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: Application to the tectonic history of the Straight Creek fault: Geological Society of America Bulletin, v. 95, p. 26–44.

Tarduno, J.A., and Cottrell, R.D., 1997, Paleomagnetic evidence for motion of the Hawaiian hotspot during formation of the Emperor seamounts: Earth and Planetary Science Letters, v. 153, p. 171–180.

Tarduno, J.A., Duncan, R.A., Cottrell, R.D., and Scholl, D.W., 2001, Motion of Hawaiian hotspot during formation of the Emperor Seamounts: Initial results of ODP Leg 19: Eos (Transactions, American Geophysical Union), v. 87, no. 47, p. F1116.

Taylor, B., and Exon, N.F., 1987, An investigation of ridge subduction in the Woodlark-Solomons region: Introduction and overview, *in* Taylor, B., and Exon, N.F., eds., Marine geology, geophysics, and geochemistry of the Woodlark Basin–Solomon Islands: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 7, p. 1–24.

Thorkelson, D.J., 1989, Eocene sedimentation and volcanism in the Fig Lake graben, southwestern British Columbia: Canadian Journal of Earth Sciences, v. 26, p. 1368–1373.

Thorkelson, D.J., 1996, Subduction of diverging plates and the principles of slab window formation: Tectonophysics, v. 255, p. 47–63.

Thorkelson, D.J., and Taylor, R.P., 1989, Cordilleran slab windows: Geology, v. 17, p. 833–836.

Trehu, A.M., Asudeh, I., Brocher, T.M., Luetgert, J.H., Mooney, W.D., Nabelek, J.L., and Nakamura, Y., 1994, Crustal architecture of the Cascadia forearc: Science, v. 265, p. 237–243.

Umhoefer, P., and Schiarizza, P., 1996, Latest Cretaceous to early Tertiary strike-slip faulting on the Yalakom fault system, southeastern Coast Belt, British Columbia: Geological Society of America Bulletin, v. 108, p. 768–785.

Wells, R.E., Engebretson, D.C., Snavely, P.D., and Coe, R.S., 1984, Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington: Tectonics, v. 3, p. 274–294.

Wells, R.E., Snavely, P.D., MacLeod, N.S., Kelly, M.M., Parker, M.J., Fenton, J.S., and Felger, T.J., 1995, Geologic map of the Tillamook Highlands, northwest Oregon Coast Range: A digital database: U.S. Geological Survey Open-File Report 95–670, http://wrgis.wr.usgs.gov/open-file/of95–670/.

Wells, R.E., Jayko, A.S., Niem, A.R., Black, G., Wiley, T., Baldwin, E., Molenaar, K.M., Wheeler, K.L., DuRoss, C.B., and Givler, R.W., 2000, Geologic map and database of the Roseburg 30°60′ quadrangle, Douglas and Coos Counties, Oregon: U.S. Geological Survey Open-File Report 00–376.

Whitney, D.L., Miller, R.B., and Paterson, S.R., 1999, *P-T-t* evidence for mechanisms of vertical tectonic motion in a contractional orogen: Northwestern US and Canadian Cordillera: Journal of Metamorphic Geology, v. 17, p. 75–90.

Wood, D.J., Stowell, H.H., Onstott, T.C., and Hollister, L.S., 1991, $^{40}Ar/^{39}Ar$ constraints on the emplacement, uplift, and cooling of the Coast Plutonic Complex sill, southeastern Alaska: Geological Society of America Bulletin, v. 103, p. 849–860.

Wooden, J.L., and Box, S.E., 1996, Contrasting inherited zircon populations in an Eocene vs. an Early Cretaceous intrusive associated with the eastern Kettle metamorphic core complex, NE Washington: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. 444.

Woodsworth, G.J., Anderson, R.G., Armstrong, R.L., Struik, L.C., and Van der Heyden, P., 1992, Plutonic regimes, *in* Gabrielse, H., and Yorath, C.J., eds., Geology of the Cordilleran orogen in Canada: Boulder, Colorado, Geological Society of America, Geology of North America, v. G-2, p. 493–531.

Wortel, M.J.R., and Spakman, W., 2000, Subduction and slab detachment in the Mediterranean-Carpathian region: Science, v. 290, p. 1910–1917. Correction: 2001, Science, v. 291, p. 437.

Yoshioka, S., and Wortel, M.J.R., 1995, Three-dimensional numerical modeling of detachment of subducted lithosphere: Journal of Geophysical Research, v. 100, p. 20,223–20,244.

Zumsteg, C.L., Himmelberg, G.R., Karl, S.M., and Haeussler, P.J., 2000, High-temperature/low-pressure metamorphism within the fore arc on Baranof Island, southeast Alaska: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-151.

Manuscript Received by the Society 14 February 2002
Revised Manuscript Received 27 December 2002
Manuscript Accepted 5 January 2003

Printed in the USA