Fore-arc migration in Cascadia and its neotectonic significance

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ABSTRACT

Neogene deformation, paleomagnetic rotations, and sparse geodetic data suggest the Cascadia fore arc is migrating northward along the coast and breaking up into large rotating blocks. Deformation occurs mostly around the margins of a large, relatively aseismic Oregon coastal block composed of thick, accreted seamount crust. This 400-km-long block is moving slowly clockwise with respect to North America about a Euler pole in eastern Washington, thus increasing convergence rates along its leading edge near Cape Blanco, and creating an extensional volcanic arc on its trailing edge. Northward movement of the block breaks western Washington into smaller, seismically active blocks and compresses them against the Canadian Coast Mountains restraining bend. Arc-parallel transport of fore-arc blocks is calculated to be up to 9 mm/yr, sufficient to produce damaging earthquakes in a broad deformation zone along block margins.

INTRODUCTION[1]

Oblique subduction of the Juan de Fuca plate northeastward beneath North America has created a complex, seismically active convergent margin and volcanic arc in the Pacific Northwest (Fig. 1). Such oblique convergence commonly produces arc-parallel migration of the fore arc (e.g., McCaffrey, 1994) and often creates an additional seismic hazard from the relative motions of fore-arc blocks. In southwest Japan, one of the most devastating earthquakes of recent times occurred in Kobe (1995, $M_w = 6.9$) on a shallow strike-slip fault, possibly accommodating coast-parallel transport of the fore arc (Kanamori, 1995; Hashimoto and Jackson, 1993). Although great subduction earthquakes have occurred along the Cascadia margin (Atwater and Hemphill-Haley, 1997), the potential for damaging upper-plate, or crustal, earthquakes is poorly known because of the short record of historical seismicity, sparse data on regional deformation rates, and poor exposure of active structures. In this paper, we examine evidence for contemporary arc-parallel migration of the Cascadia fore arc and discuss the implications for damaging crustal earthquakes.

Northward motion of the Cascadia fore arc has been inferred from clockwise paleomagnetic rotations and translations of Cenozoic coastal terranes (e.g., Beck, 1984), from geologic evidence for north-south shortening in the Washington fore arc (Snavely and Wells, 1996; McCrory, 1996), and from modeling of plate-boundary forces (Wang, 1996). Northward motion of the Coast Range averaging 6 mm/yr is inferred from the smoothly increasing rotation of 12 Ma Columbia River Basalt flows toward the coast (England and Wells, 1991), and as much as 17 mm/yr northward transport of the accretionary complex may be occurring offshore at the deformation front (McCaffrey and Goldfinger, 1995). Pezzopane and Weldon (1993) linked translation of the Cascadia fore arc to motion of the Sierra Nevada block, which is translating northwest at 1 cm/yr as a result of Pacific–North America dextral shear and Basin and Range extension (Argus and Gordon, 1991). Building on earlier paleomagnetic block models, Walcott (1993) linked rotation of the Cascadia fore arc to translation of the Sierra Nevada in an integrated model for Neogene deformation of the Cordillera.

These simple block models provide a useful framework for analyzing current motions of the Cascadia fore arc and its effect on upper plate seismicity and volcanism. We assume that Neogene coastal rotations are still occurring today and can be linked to geodetic data for current motion of the Sierra Nevada. We can then calculate new Euler poles for the Oregon fore-arc block and determine its motion with respect to North America.

CASCADIA FORE-ARC BLOCKS

The Cascadia fore arc lies between the plate boundary megathrust and the seismically and volcanically active arc. Along strike, the fore arc can be subdivided into Sierra Nevada, Oregon, and Washington segments based on contrasting patterns of Neogene deformation (Figs. 1 and 2), seismicity and volcanism (Fig. 2), and crustal structure (Fig. 3).

Sierra Nevada Block

The Sierra Nevada block includes the Sierra Nevada–Great Valley of California and is bounded by the Basin and Range Province and the San Andreas–Coast Range fault system (Argus and Gordon, 1991). We extend the block northwest along strike to the Oregon border, the approximate hinge line in the arcuate trend of the relatively aseismic Klamath Mountains. The

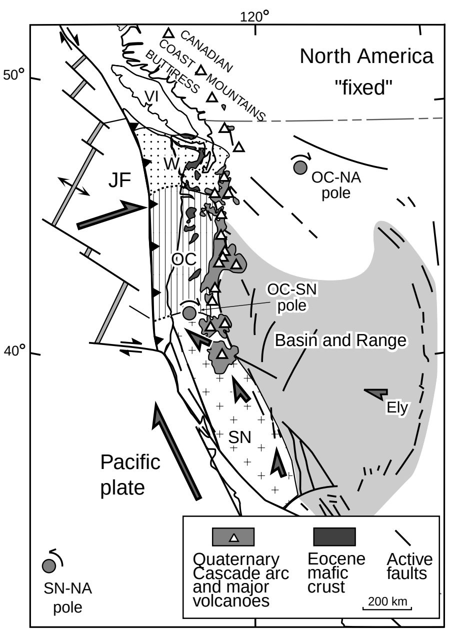

Figure 1. Tectonic setting of Cascadia. Juan de Fuca plate (JF) is subducting (barbed fault) beneath North America. Migrating Cascadia fore-arc terrane divided into Washington (W), Oregon Coastal (OC), and Sierra Nevada blocks (SN). "Instantaneous" Euler rotation poles shown for SN relative to North America (NA), OC-SN, and OC-NA. VI—Vancouver Island. (Modified from Argus and Gordon, 1991; Pezzopane and Weldon, 1993; Walcott, 1993.)

[1]After this paper was accepted for publication, we learned that the Sierra Nevada–North America rotation pole has been revised (Donald Argus and Richard Gordon, written commun., 1998). Using the revised pole, we have calculated a new pole for Oregon Coast motion with respect to North America (lat 46.867°N, long 119.962°W, ang. vel. –1.168°/m.y.). Coast Range motion (Fig. 4) north of 45°N becomes 5°–20° more northerly and slows by 14%–38% (e.g., new velocity is 7 mm/yr, N19°W at Astoria, Oregon, instead of 8 mm/yr, N37°W). The fit to the geology is improved, and our conclusions are unchanged.

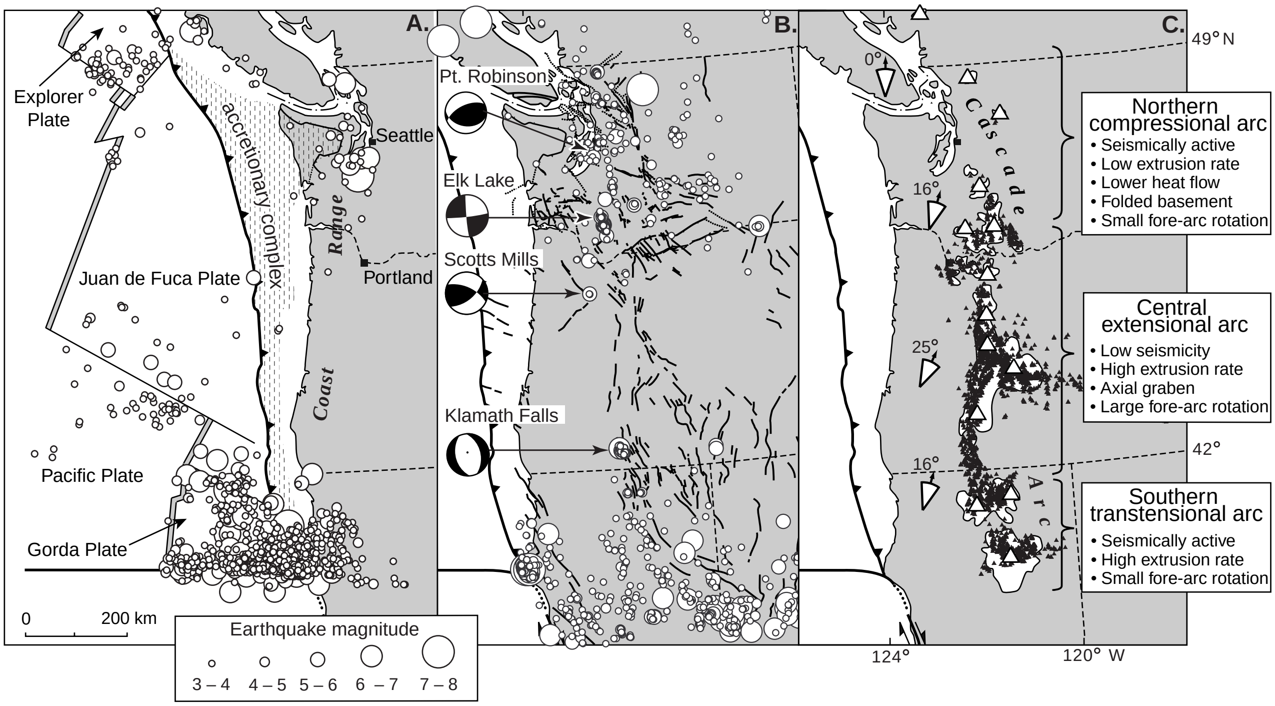

Figure 2. Cascadia earthquakes, faults, volcanoes, and fore-arc rotation (see text). A: Lower plate seismicity. B: Upper plate seismicity, recent focal mechanisms (M_w > 5), and late Cenozoic faults. C: Quaternary arc volcanism—white; major volcanoes—open triangles; post–5 Ma volcanic vents—filled triangles; fore-arc rotations with uncertainties—arrows (Pezzopane and Weldon, 1993; Sherrod and Smith, 1990; Guffanti and Weaver, 1988; Wells, 1990; Wiley et al., 1993; Madin et al., 1993).

block boundaries thus include the southernmost Cascadia subduction zone and the seismically active southern Cascade arc (Figs. 1 and 2). Although Neogene paleomagnetic rotations are small (Beck et al., 1986), very long baseline interferometry (vlbi) measurements indicate the northern end of the Sierra Nevada block is moving N50°±5°W at 11 ± 1 mm/yr with respect to North America (Argus and Gordon, 1991).

Oregon Fore-Arc Block

The Oregon fore arc is largely underlain by the accreted basalt seamount terrane of Siletzia (Snavely and Wells, 1996). As much as 35 km thick (Trehu et al., 1994), its extent can be inferred from broad gravity and magnetic highs in the Coast Range (Figs. 1 and 3). We extend the Oregon block southward to the Oregon border based on Tertiary onlap relations in the Klamath Mountains and the lack of active faulting and seismicity. During the Cenozoic, the Oregon block has been rotating clockwise with respect to stable North America at about 1.5°/m.y. (e.g., Magill et al., 1982). An active accretionary fold and thrust belt lies outboard of the Oregon block along the subduction zone (Goldfinger et al., 1992), and an extensional volcanic arc characterized by high heat flow (Blackwell et al., 1990) and volcanic eruption rates (Sherrod and Smith, 1990) separates the fore arc from the Basin and Range.

Washington Fore-Arc Block

In the Washington fore arc, gravity and magnetic data outline smaller mafic blocks of Siletzia, consistent with Neogene deformation along block boundaries and distributed shear rotations (England and Wells, 1991). On Vancouver Island, Neogene rotations are negligible (Irving and Brandon, 1990), and at Penticton in southern British Columbia, vlbi indicates no resolvable present-day motion with respect to fixed North America (2 ± 3 mm/yr, Argus and Gordon, 1996). East-west–trending uplifts and associated thrust or reverse faults like the active Seattle fault (Johnson et al., 1994) accommodate north-south shortening in the Washington fore arc, analogous to the Yakima fold belt in the back arc, and suggest compression by northward-moving coastal terranes against the Canadian Coast Mountains restraining bend. Crustal earthquakes 10–30 km deep are concentrated beneath the Puget Lowland and arc, and appear correlated with Wadati-Benioff zone seismicity (Fig. 2). Strike-slip and thrust focal mechanisms with north-south compressive axes are common, a style of faulting consistent with late Cenozoic deformation. Northwest-trending, right-stepping zones of seismicity with right-lateral focal mechanisms indicate dextral shear in the arc (Weaver and Smith, 1983; Stanley et al., 1996). Quaternary volcanic eruption rates and vent abundance decrease north of Mount Rainier (Fig. 2C), and isolated volcanoes rest on the folded and uplifted compressional arc basement (Smith, 1993).

KINEMATIC MODEL

Our model for migration and breakup of the Cascadia fore-arc blocks is shown in Figure 4. We assume the Canadian buttress is relatively fixed on the basis of vlbi results from Penticton, British Columbia, which indicate no resolvable change of position with respect to stable North America (2 ± 3 mm/yr northward; Argus and Gordon, 1996). In contrast, vlbi results from northern California indicate west-northwest translation of the north end of the Sierra Nevada block at 11 ± 1 mm/yr N50°±5°W toward southwest Oregon (e.g., Argus and Gordon, 1991). Differential motion between California and Penticton is absorbed by clockwise rotation of the Oregon fore-arc block, which is linked to west-northwest motion of the Sierra Nevada by and Oregon Coast–Sierra Nevada Euler pole at the hinge between the two blocks (λ 42°N; ϕ –123°W; ϖ –1.5°/m.y.). Adding this pole to the Sierra Nevada–North America pole of Argus and Gordon (1991), we determined the Oregon Coast–North America pole (λ 48.5°N, ϕ –118.7°W, ϖ –0.91°/m.y.) and calculated the motion of the Oregon fore-arc block with respect to North America. As a result, the southern end of the rotating Oregon block moves toward the trench at Cape Blanco at about 12 ± 1 mm/yr, thus transferring much of the Sierra Nevada displacement to the southern subduction zone. Because of its rotation (1.5°/m.y. ± 0.5°), the northern end near Astoria moves north-northwest at about 9 mm/yr with respect to North America. Quaternary extension in the Basin and Range and extensional arc volcanism inboard of the rotating block thus decrease northward, while dextral slip and north-south compression increase northward.

Because of northward-moving Oregon coastal block, the Washington fore arc is breaking up into small blocks which are being deformed against the Coast Mountains buttress. North-south shortening in the Washington and northernmost Oregon fore arc could be 7–9 mm/yr, if the motion is absorbed internally. Uplift in the Olympic Mountains could in part result from the north-south shortening (e.g., Walcott, 1993). The Portland Hills, St. Helens, and West Rainier seismic zones may together act as a diffuse transfer zone between northward moving coastal blocks and the continental interior (e.g., Weaver and Smith, 1983; Stanley et al., 1996).

Behind the Oregon block, Holocene Oregon Basin-Range extension of 4 ± 2 mm/yr in a N60°±30°W direction (Pezzopane and Weldon, 1993)—when added to vlbi displacements for Ely, Nevada, with respect to stable North America (4.9 ± 1.3 mm/yr at 262°; Dixon et al., 1995) and arc spreading rates of 1 mm/yr derived from heat flow—gives a spreading rate of about 10 mm/yr across the northern Basin and Range, consistent with vlbi data for the Sierra Nevada and paleomagnetically determined extension rates (e.g., Magill et al., 1982). In the absence of abundant seismicity along the trailing edge of the rotating block, magmatism may accommodate an important part of the extensional strain as far north as Mount St. Helens (e.g., Parsons and Thompson, 1991).

DISCUSSION AND CONCLUSIONS

Our calculated fore-arc motions represent the integrated displacements over many subduction zone seismic cycles. The apparent contradiction between northeast-directed geodetic shortening in the fore arc that is subparallel to the convergence direction (Fig. 3) and the long-term northwest motion of fore-arc blocks can be explained if the geodetic signal in the fore arc is dominated over the short term by elastic coupling along the Cascadia subduction zone (Wang et al., 1995). When slip occurs on the subduction zone, the fore arc will likely rebound in a direction more normal to the margin, and the accumulated difference should approximate the arc-parallel migration rate of the fore arc.

Overall, the calculated motions are consistent with the observed northward change in Neogene deformation from transtension to transpression and the concomitant change in the Cascade arc magmatism. The motions are also consistent with north-south compressive axes indicated by upper plate earthquake focal mechanisms (Fig. 2) and the overall northward decrease in seismic strain rates calculated from upper-plate earthquakes (Pezzopane and Weldon, 1993).

Along the subduction zone, Oregon block motions increase the convergence rate near Cape Blanco; thus along-strike variation in convergence expected from the Juan de Fuca–North America rotation pole (Wilson, 1993) is mini-

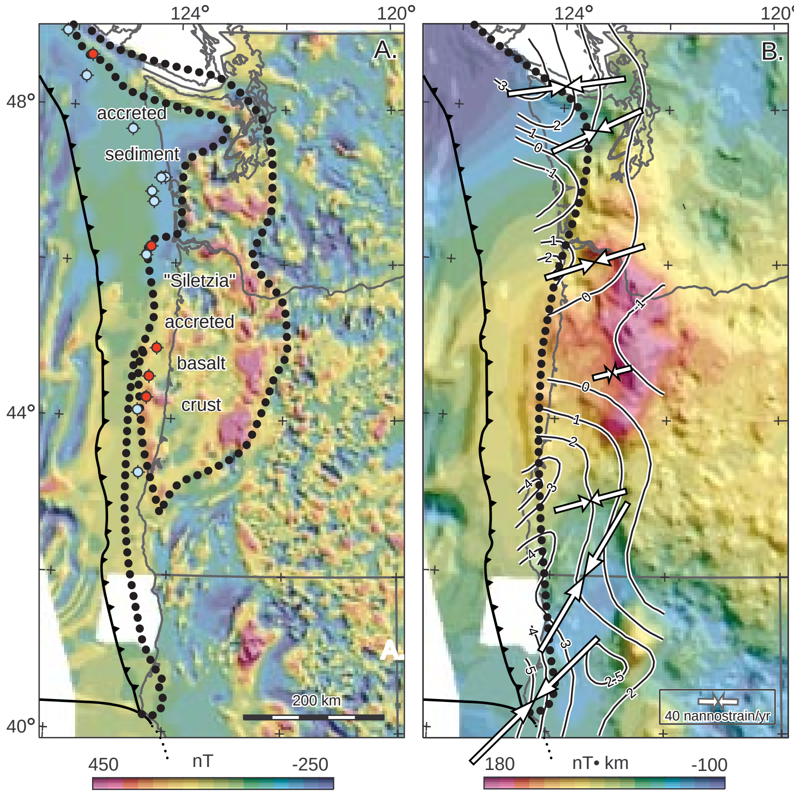

Figure 3. Magnetic and pseudogravity anomalies in the Cascadia fore arc. A: Siletzia, accreted basalt basement shown by magnetic high and offshore wells (filled circles) bottoming in basalt basement (red) and sediment (blue). Accreted sediments (magnetic low) outboard of Siletzia extend south to Mendocino triple junction. B: Pseudogravity anomaly (gravity that would be observed if magnetization were replaced by mass in 1:1 proportion) reflects total volume of Siletzia and coincides with low current uplift and margin contraction (contours in mm/yr, Mitchell et al., 1994; Murray and Lisowski, 1994, and 1998, written commun.) representing elastic strain accumulation above the locked subduction zone. Eastward limit of coupling (dotted) from Hyndman and Wang (1995).

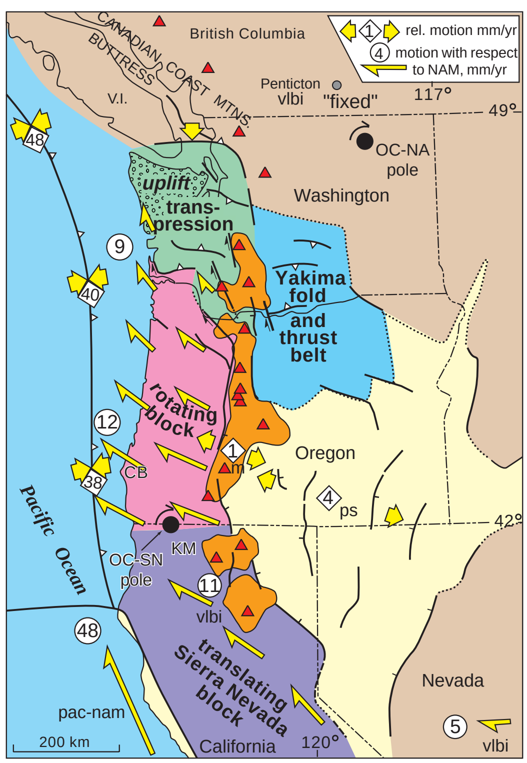

Figure 4. Velocity field for Cascadia fore arc calculated from OC-NA pole. Oregon block (pink) rotating at Neogene paleomagnetic rate is linked to Sierra Nevada block moving at vlbi rate by Euler pole (OC-SN) in Klamath Mountains (KM). Extensional arc forms along trailing edge of Oregon fore-arc block which absorbs Sierra Nevada displacement by rotating over trench at Cape Blanco (CB). North end of Oregon block deforms Washington fore arc (green) against Canadian buttress, causing north-south compression, uplift, thrust faulting, and earthquakes. Rates from very long baseline interferometry (vlbi); paleoseismology (ps); magmatic spreading (m); Pacific–North America motion (pac-nam); other symbols as in Figure 1.

mized (Fig. 4). Contemporary coastal uplift that is interpreted as elastic strain accumulation above the locked subduction zone fault (Mitchell et al., 1994) is variable and may in part reflect the composition of fore-arc blocks. Areas of maximum coupling with the slab inferred from coastal uplift coincide with accreted sediments beneath the Olympic Peninsula and south of Cape Blanco (Fig. 3). The intervening region of low uplift, interpreted to be the result of a narrower locked zone offshore, coincides with Siletzia, the thick mafic crust of the Coast Range. It is possible that the sedimentary accretionary wedge provides a smoother interface between plates, resulting in larger areas of coupling. Alternatively, the thick mafic crust of coastal Oregon may either force the slab to dip more steeply, or may prevent cooling of the slab, thus minimizing coupling.

Arc-parallel motion in the northern Cascadia fore arc is significant and similar to that determined from geodetic data by Hashimoto and Jackson (1993) for dextral slip along the Median Tectonic Line in southwest Japan. Given Cascadia fore-arc motions of 7 to 9 mm/yr, one might expect large upper-plate earthquakes to occur in the fore arc over historically significant time periods. Four M = 6.5–7.4 crustal earthquakes have occurred in the past 125 yr, but none have occurred in the Seattle-Portland urban corridor (Rogers et al., 1996). Evidence for 7 m of uplift along the Seattle fault indicates that a major event (est. M = 7) did occur in the shallow crust beneath Seattle about 1100 yr ago (Bucknam et al., 1992). Although rates of Cascadia fore-arc motion suggest that damaging earthquakes might occur in the future, estimating the probability of future events awaits geodetic testing of the model and determination of the location, length, and slip rates of crustal faults.

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