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Tectonics and Seismicity of the Southern Washington Cascade Range

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Abstract Geophysical, geological, and seismicity data are combined to develop a transpressional strain model for the southern Washington Cascades region. We use this model to explain oblique fold and fault systems, transverse faults, and a linear seismic zone just west of Mt. Rainier known as the western Rainier zone. We also attempt to explain a concentration of earthquakes that connects the northwest-trending Mount St. Helens seismic zone to the north-trending western Rainier zone. Our tectonic model illustrates the pervasive effects of accretionary processes, combined with subsequent transpressive forces generated by oblique subduction, on Eocene to present crustal processes, such as seismicity and volcanism.

Introduction

The southern Washington Cascades contains Mt. Rainier, the most massive of the volcanoes in the Cascade Range magmatic arc (Fig. 1). Mt. Rainier is part of the triangle of large stratovolcanoes in southern Washington that includes Mount St. Helens and Mt. Adams. Mount St. Helens experienced a cataclysmic eruption in 1980 and is apparently younger than Mt. Rainier and Mt. Adams, both of which exhibit more rounded profiles than the pointed, pre-1980 Mount St. Helens. Mt. Rainier towers above the highly populated Puget Sound region to the west and the possibility of future eruptions of Mt. Rainier is an important geologic hazard that needs to be fully evaluated.

There is also the possibility for damaging earthquakes in the Mt. Rainier region, and accurate tectonic models are needed to evaluate the potential for such hazards. Our goal in this article is to develop a testable tectonic model required to understand seismicity patterns observed in the southern Washington Cascade Range, such as linear belts of seismicity associated with Mount St. Helens [St. Helens zone (SHZ), Fig. 1] and in the area west of Mt. Rainier [western Rainier zone (WRZ), Fig. 1]. We conclude in this report that seismicity is driven by transpressive deformation related to oblique subduction. Transpression and transtension (Sanderson and Marchini, 1984) have been described as a combination of simple shear and pure shear and "are reasonable kinematic models for areas of oblique plate interaction" (Teyssier *et al.,* 1995). Transpression occurs with a large normal component of subduction, and transtension occurs with a small normal component of subduction.

Understanding the WRZ and the SHZ is important to assessment of earthquake hazards in the region and in evaluation of geologic hazards posed by Mt. Rainier. Part of the research for this article was stimulated by the selection of Mt. Rainier as a Decade Volcano for the 1990s (Swanson *et al.,* 1992) by the International Association of Volcanology and Chemistry of the Earth's interior.

Geology of Western Washington

The Puget Sound region and the western flank of the Cascade Range in southwestern Washington occupy a complex tectonic setting along the margin of two distinct crustal blocks. Crust in the eastern block beneath the southwest Washington Cascades is composed of Mesozoic and older accreted terranes, volcanic arcs, and underplated magmatic rocks. This older accreted crust is well exposed in Washington's North Cascades (Fig. 1) but plunges southward below Tertiary volcanic rocks in the southern Cascades; the southernmost exposures of these basement rocks occurs in the Rimrock inlier southeast of Mt. Rainier (Miller, 1989). This basement complex was cut by numerous dextral strike-slip faults during a transtensional deformation event in the Eocene when several pull-apart basins formed. Master faults include the Straight Creek fault (Vance and Miller, 1981; Tabor *et al.,* 1984) and the hypothetical Puget fault (Johnson, 1984, 1985). Volcanoes of the Cascade Range (Fig. 1) represent the magmatic arc associated with post-40 Ma subduction of the Juan de Fuca plate and its predecessors.

Basement in the Coast Range block to the west, which we refer to as Siletzia (after Irving, 1979), consists of middle Eocene marine basaltic rocks (Fig. 1). In western Washington, the formation name for the basaltic rocks is the Crescent formation. These rocks are believed to have formed in a continental-margin rift setting (Wells *et al.,* 1984; Snavely, 1987; Babcock *et al.,* 1992), possibly associated with a hot spot or leaky transform system. In southwest Washington, this volcanic basement is exposed along the southern part of the Olympic Peninsula and in the Black Hills and Willapa Hills (Fig. 1). Elsewhere in the Coast Range, it forms the basement for Tertiary forearc basins. Gravity and magnetic data (Finn, 1990; Finn *et al.,* 1991; Finn, 1995) indicate that the dense, highly magnetic mafic rocks of Siletzia consist of

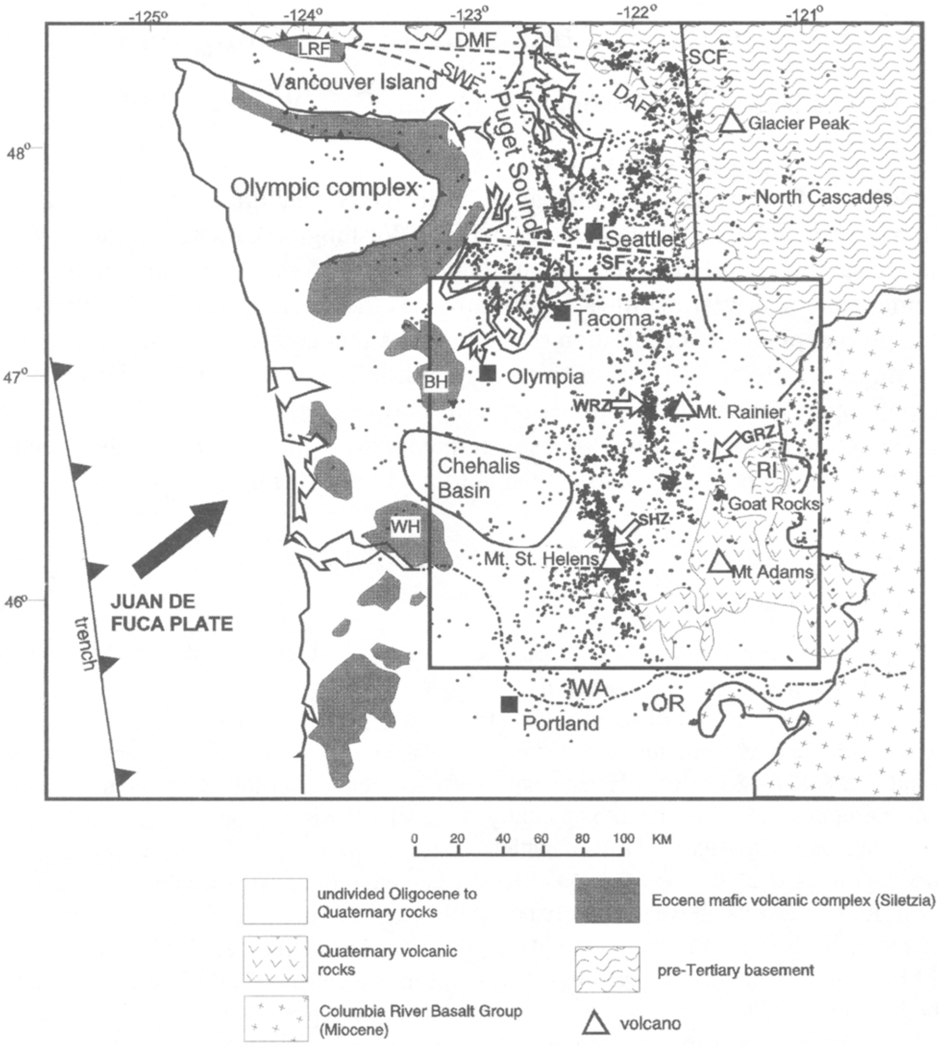


Figure 1. Simplified geological map of western Washington showing volcanoes and earthquakes (small circles). Earthquakes are well-located events from the University of Washington catalog for the period 1984 to 1994. The box in the center of the figure is an area of detail utilized in Figures 3, 7, 8, and 10. SHZ = St. Helens seismic zone; WRZ = western Rainier seismic zone; GRZ = Goat Rocks zone; RI = Rimrock inlier of Jurassic-Cretaceous basement rocks; BH = Black Hills; WH = Willapa Hills; SCF = Straight Creek fault; LRF = Leech River fault; SWF = southern Whidbey Island fault; SF = Seattle fault; DMF = Devils Mountain fault; DAF = Darrington fault. The bold arrow inboard from the subduction zone trace (trench) represents the approximate convergence vector between the Juan de Fuca plate and the North American plate (Engebretson *et al.,* 1985).

many discrete blocks, with the largest occupying the central Coast Range of Oregon (Fig. 2). Wells and Coe (1985) interpret that the mafic blocks in southwestern Washington are bounded by northwest- and west-striking thrust faults that formed in response to the north-directed component of oblique subduction. Paleomagnetic studies (Wells *et al.,* 1984) indicate that most Siletzia blocks have been rotated clockwise, both collectively and individually, by a combination of dextral shear (related to block-bounding faults) and basin and range spreading (Wells and Coe, 1985; Wells and Heller, 1988). Pratt *et al.* (1994) interpret that a "Puget Lowland" thrust sheet cuts the volcanic basement of the Coast Range volcanic province and that a decollement occurs at the base of the volcanic basement. They interpret that the numerous Siletzia blocks evident on the gravity and magnetic data (Fig. 2) and discussed earlier by Wells and Coe (1985) are all part of large thrust sheet with the blocks "popping up" along thrust faults rooted in the regional decollement. We infer from the gravity and magnetic data (Fig. 2) that there is considerable variation in the thickness of the mafic complex from Oregon into Washington. Tertiary sedimentary basins may have formed where north-south con-

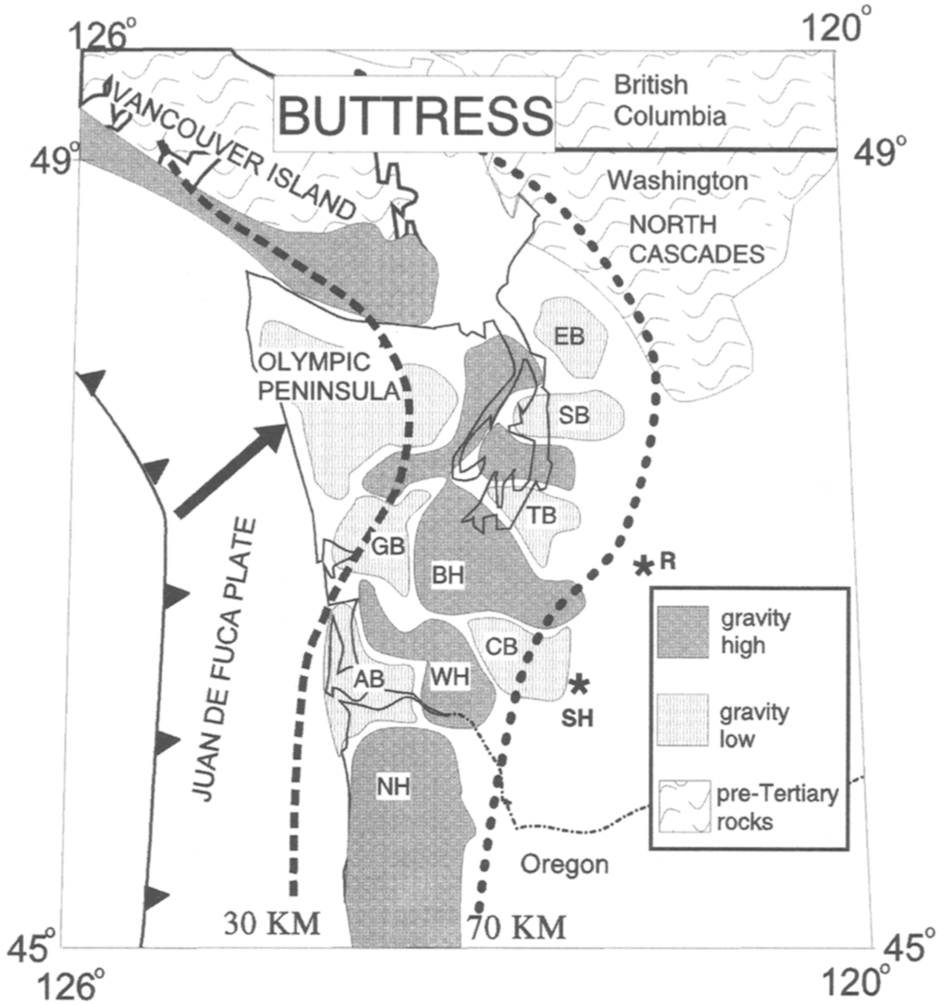


Figure 2. Bouguer gravity anomalies in western Washington and northwestern Oregon, taken from data supplied by C. Finn (written comm., 1995), showing the blocklike character of Siletzia crust in the Pacific Northwest Coast Ranges. Highs are values primarily greater than 10 milligals, and lows are values generally less than -20 milligals. Dashed contours are interpreted depths to the top of the subducting Juan de Fuca plate from Crosson and Owens (1987), with the 70-km contour extrapolated by us from their 30-, 40-, 50-, and 60-km contours. A buttress is formed by the bend in the subduction zone and the location of pre-Tertiary basement in the North Cascades and Vancouver Island. R = Mt. Rainier; SH = Mount St. Helens; EB = Everett Basin; SB = Seattle Basin; TB = Tacoma Basin; GB = Grays Harbor Basin; CB = Chehalis Basin, AB = Astoria Basin; BH = Black Hills; WH = Willapa Hills; NH = Nehalem Hills. The bold arrow is the approximate current direction of subduction of the Juan de Fuca plate and the subduction zone trench trend is shown by the thrust symbol.

traction acted to downwarp the thinner portions of the mafic complex or where faulting produced tectonic subsidence.

The group of Siletzia blocks is apparently moving northward along a broad, distributed dextral shear zone along the eastern flank of the Coast Range province into the northern Puget Sound region where they encounter a buttress (Fig. 2) formed by pre-Tertiary basement in Vancouver Island and the North Cascades. The dashed contours in Figure 2 represent depths to the top of the subducting Juan de Fuca plate and a bend in the subduction zone noted by Crosson and Owens (1987). The combined effect of the buttress and the bend in the subduction zone is to jam up the mafic blocks in the Puget Sound area.

This article describes a portion of the broad boundary zone between the pre-Tertiary and Coast Range basement blocks in the southwest Washington Cascades. Stanley *et al.* (1992, 1994) interpret that much of this area is underlain by a thick upper Cretaceous to middle Eocene sedimentary complex. The evidence for this sedimentary complex is a large, buried, high-conductivity feature called the southern Washington Cascades conductor (SWCC, Fig. 3). The upper part of the interpreted sedimentary complex is thought to

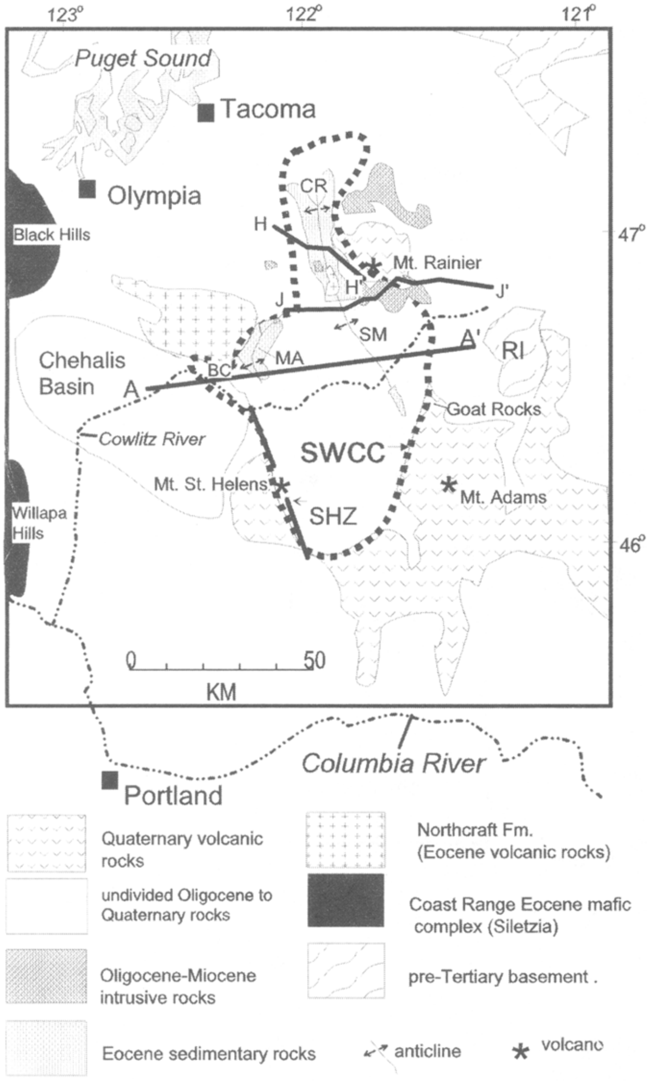


Figure 3. Details of southern Washington Cascades area showing simplified geology (modified from Walsh *et al.*, 1987), outline of southern Washington Cascades conductor (SWCC), geological-geophysical profile AA′, and two magnetotelluric (MT) profiles JJ′ and HH′. MA = Morton anticline; BC = Bear Canyon; CR = Carbon River anticline; SM = Skate Mountain anticline; SHZ = St. Helens zone; RI = Rimrock inlier.

have been deposited in an Eocene pull-apart basin system (Stanley *et al.*, 1992, 1994; Johnson and Stanley, 1995) partially contemporaneous with the Siletzia basalts. Deeper sections of the SWCC along its eastern margin may be related to an accretionary prism/forearc basin complex.

The broad boundary zone and the area underlain by the SWCC experienced significant Oligocene to present deformation. This deformation includes extensive northwest-trending fold sets and thrusts (Fiske *et al.*, 1963; Gard, 1968) concentrated in two significant anticlinal structures: the Carbon River-Skate Mountain anticline and the Morton anticline (Schasse, 1987; Walsh *et al.*, 1987), which reflect a broad history of strain-related uplift. These anticlines are complex structural arches on which Oligocene and younger volcanic rocks have been uplifted and eroded, exposing Eocene sedimentary rocks; their development probably reflects the integrated effects of mostly contractional strain. The more numerous, smaller anticlines and synclines that parallel, cross, and are superimposed on these structural arches represent the effects of incremental strain, as discussed later with our models (see section entitled Tectonic Model for the Southern Washington Cascade Range).

The combined Carbon River-Skate Mountain anticline is traceable by outcrops of Eocene sedimentary rocks, an aeromagnetic low (Stanley *et al.*, 1987) caused by thinning of the volcanic rocks, and by seismicity trends that we discuss below. Folded Eocene sedimentary rocks in the Carbon River anticline typically dip 60° or more, and overturned beds are common. Gard (1968) recognized two fault sets in the anticline: (1) high-angle reverse and normal faults that strike north-northwest and parallel fold axes and (2) normal faults that cross the north-northwest fold axes at an oblique angle (30° to 40°) and postdate the fold-parallel faults. These younger normal faults were observed to trend east-northeast and offset Pleistocene glacial deposits in some instances. Tight folding and steep faulting are also evident in industry seismic data obtained from the Carbon River anticline, including the northward extension of the structure beneath the Puget Lowland (Stanley *et al.*, 1994; Johnson *et al.*, 1994). Both the fold-parallel faults and the younger fold-oblique normal faults have as much as 300 to 500 m of displacement. Several andesite dikes, sills, and plugs of probable Miocene age intrude the Carbon River anticline and are mostly aligned parallel to the strike of the anticline (Walsh *et al.*, 1987; Schasse, 1987). Formation of structures within the anticlines may have begun in latest Eocene or Oligocene (Fiske *et al.*, 1963; Gard, 1968; Buckovic, 1974) and has continued to present, as indicated by the current seismicity. The western Rainier seismic zone (WRZ) is centered on the north-trending portion of the Carbon River-Skate Mountain anticline.

The Morton anticline is a complex structural arch along the western margin of the SWCC (Fig. 3). It has been studied extensively as a possible hydrocarbon play by Stanley *et al.* (1994) and Johnson and Stanley (1995). Surface outcrops and interior fold axes suggest that the Morton anticline has been highly deformed by transpressive forces since initial formation. The southern 40% of the surface expression of the anticline trends approximately N30°W (Fig. 3; Walsh *et al.*, 1987; Johnson and Stanley, 1995), but the northern 60% of the surface trends N30°E. Stanley *et al.* (1994) interpret that this variation in azimuth results from increased contraction of the deformable SWCC complex in the northern portion of this zone. The area west of the Morton anticline is underlain by middle to upper Eocene Northcraft formation volcanic rocks (Fig. 3) and is coincident with a large gravity (Fig. 2) and magnetic anomaly. The gravity anomaly (Fig.

2) extends southeastward from the Black Hills outcrops (Fig. 1) of Crescent basement.

Portions of the structural zone occupied by the SWCC are now seismically active in response to oblique subduction. The Mount St. Helens seismic zone (SHZ) of Weaver and Smith (1983) is apparently coincident with the contact between the SWCC on the east and the mafic Coast Range (Siletzia) basement (Stanley *et al.,* 1992) on the west (Fig. 3). This coincidence is important for three reasons. First, it indicates that crustal block boundaries, perhaps established in early to middle Eocene, may play an important role in present fault motions. Second, the crustal-block hypothesis and the strain models that we outline in this article provide additional information for estimating credible maximum earthquake magnitudes along the SHZ; events as large as *M* 6.5 may be possible on the SHZ (Weaver and Shedlock, 1992). Third, lacking known surface faults of Quaternary age along the SHZ, the geophysical data allow estimates of seismic hazards to be constrained by a regional structural model.

Seismicity of Western Washington

The distribution of earthquakes in western Washington is complex and includes events in the subducting Juan de Fuca plate and the crust, as illustrated in Figure 4. The cross sections show seismicity in two east–west swaths, one between 46° and 47° latitude and the other between 47° and 48° (Fig. 1). The events within the Juan de Fuca plate (Fig. 4) define the geometry of the Benioff zone beneath western Washington (Crosson and Owens, 1987; Weaver and Baker, 1988).

The cross sections of Figure 4 show that crustal seismicity in western Washington is concentrated in the Puget Sound and Cascades region at depths of less than 25 km. In a later section of this article, selected cross sections reveal that along steep fault zones in western Washington, crustal earthquakes are distributed between the near-surface and 20 to 25 km. Away from steep fault zones, the earthquakes are concentrated in the 15- to 25-km-depth range. The maximum depths of crustal earthquakes in the region west of the Cascade Range occur at the approximate base of Siletzia crust, as interpreted from MT soundings, gravity and magnetic models, and seismic-reflection/refraction data (Finn, 1990; Stanley *et al.,* 1987; Clowes *et al.,* 1988).

The concentration of crustal earthquakes at 15- to 25-km depths may be related to several factors. One factor may be instantaneous strain generated within the lower part of Siletzia crust as it slides over material beneath it in the lower crust. Geologic studies in the Olympic Peninsula (e.g., Tabor and Cady, 1978) and geophysical interpretations (Stanley *et al.,* 1987; Clowes *et al.,* 1988) suggest that the lower crust beneath Siletzia in western Washington and southern Vancouver Island consists of underplated Eocene and younger sedimentary rocks and slices of oceanic crust. Such imbricated sedimentary and oceanic rocks have very low horizontal shear strength; thus, it is not likely that Siletzia sliding over these underplated rocks produces the concentration of seismicity at depths of 15 to 25 km away from active steep faults. A decrease in depths to the bottom of crustal seismicity between Puget Sound and the Olympic Peninsula core (Fig. 4 upper) likely reflects the east-dipping thrust contact between thick post-Eocene marine sedimentary rocks in the Olympic complex and peripheral Siletzia mafic rocks (Fig. 1).

Other factors may control the depth limits and concentration of crustal earthquakes. The thermally controlled, brittle–ductile transition may be a factor in limiting seismicity depths, especially on the east end of the cross sections of Figure 4 in the Cascade Range where heat flow is high. Maximum depth to crustal earthquakes decreases to the east near the Cascade Range. Bending stresses in the lower part of Siletzia blocks may also play a role in concentrating earthquakes in the 15 to 25-km depth range. Additionally, serpentinization or other metamorphic processes stimulated by fluids released from the underlying subduction complex may also contribute to the concentration of earthquakes in the lower parts of the Siletzia mafic crust (depths of 15 to 25 km). Serpentinization is a hydration reaction that decreases density (from 3.3 gm/cm^3 in peridotite to 2.65 gm/cm^3 in serpentinite), increases volume (O'Hanley, 1992), and releases heat, since the reaction is strongly exothermic (Fyfe *et al.,* 1978). Any such volume changes would lead to strain in the lower parts of Siletzia mafic crust and could generate earthquakes. Serpentinization within the lower parts of Siletzia may be occurring only if the mafic flow units are underlain at depth by ultramafic crust. If Siletzia was formed by superposition of an offshore pull-apart structure with a leaky transform or hot spot, as postulated by Wells *et al.* (1984), then mantle-derived ultramafic rocks may comprise the lower parts of this crustal complex.

Previous studies have noted pronounced differences in the spatial distribution of crustal earthquakes in northwestern and southwestern Washington (Stanley, 1984; Ludwin *et al.,* 1992; Weaver *et al.,* 1990). In northwestern Washington, crustal events are confined to the area between the eastern Olympic Peninsula and the Quaternary volcanoes in the Cascade Range (Fig. 1), with very few earthquakes located farther east in the North Cascades. Intense earthquake activity in the Puget Sound region diminishes rapidly south of Tacoma (Fig. 1). This change may be related to increased strain in the Puget Sound area caused by the bend in the subduction zone and the buttressing effect discussed earlier.

The most significant characteristic of seismicity in the region of the major volcanoes of the southern Washington Cascades is the presence of two north- to northwest-trending linear zones of seismicity. The most prominent is the St. Helens zone (SHZ, Figs. 1 and 3), where events as large as magnitude 5.5 have recently occurred (Weaver and Smith, 1983). A second zone of seismic activity is located just west of Mt. Rainier (Fig. 1), originally referred to by Thompson (1989) as the west Rainier seismic zone and renamed the western Rainier zone (WRZ) by Weaver *et al.* (1990). Mo-

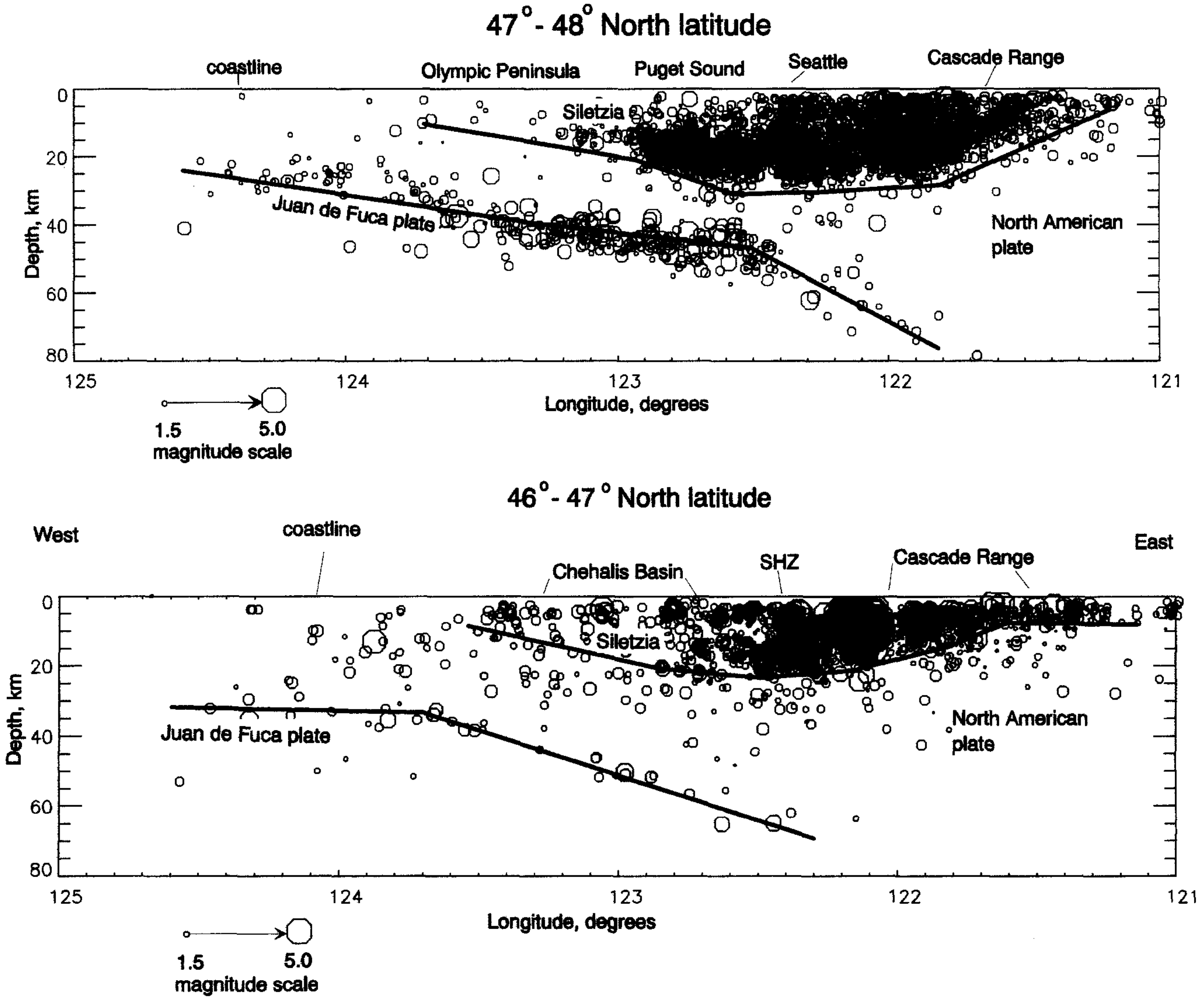


Figure 4. Seismicity sections along swaths from 46° N to 47° N (lower) and from 47° N to 48° N (upper) compiled from University of Washington catalog for 1970 to 1992. On each section, one bold line delineates the approximate top of the subducting Juan de Fuca plate as mapped by seismicity, and the shallower bold line is located approximately at the maximum depth for crustal seismicity within the overriding North American plate.

tion on the SHZ is predominantly dextral slip (Weaver and Smith, 1983). Motion on the WRZ is more complex (see focal mechanisms of Fig. 10 discussed in the section on Details of Seismicity in the Southern Washington Cascades) but also mostly dextral slip in character. Yelin and Patton (1991) have suggested that sparse seismicity near Portland (Fig. 1) may be occurring on two nearly parallel fault zones (the Portland Hills fault zone and the Frontal fault zone), but these zones are poorly defined by the available hypocenters in comparison to the SHZ and WRZ. Beyond these previously interpreted seismic zones, other linear patterns are suggested by the regional seismicity. For example, a discontinuous alignment of epicenters extends north-northwest from Goat Rocks (Fig. 1), an eroded, former Pliocene volcano southeast of Mt. Rainier. For the purposes of this article, we refer to this zone as the Goat Rocks zone (GRZ).

Geophysical Studies in the Southern Washington Cascades

The geophysical setting of Mt. Rainier and other volcanoes of the Cascade Range in southern Washington was discussed by Stanley (1983) in terms of the contractional style of the Washington Cascade Range, in contrast to the extensional style of the Oregon and northern California Cascade Range. Evidence for this contrasting style is different types of faulting, regional magnetotelluric (MT) models, and the distribution of basaltic volcanic rocks associated with extension. MT surveys in the southern Washington Cascade Range (Stanley *et al.*, 1987) delineated the SWCC (Fig. 3), which was first detected with sparse geomagnetic array measurements (Law and Booker, 1983). Detailed geomagnetic array studies by Egbert and Booker (1994) confirmed the general structure of the SWCC as determined from MT surveys and extended knowledge about regional conductivity structures in western Washington.

Lees and Crosson (1990) compiled tomographic images using local earthquakes in western Washington and found a pseudohorizontal, low-velocity body that thickened to 16 km just west of Mt. Rainier. We interpret that this low-velocity body corresponds to the SWCC. Lees and Crosson (1990) also mapped a low-velocity body beneath Mt. Rainier at depths of 9 to 25 km. They suggested that the low-velocity body beneath Mt. Rainier might be a magma chamber, but we interpret MT models from near Mt. Rainier to show conductive rocks of the SWCC in this depth range (discussed later in this section); therefore, the low velocities mapped at mid-crustal depths near Mt. Rainier may be related to sedimentary units of the SWCC.

Finn (1990) modeled gravity and magnetic data for western Washington and interpreted the eastern boundary of Siletzia as corresponding to a north–south striking gravity gradient passing through Mount St. Helens and Seattle, Washington. New detailed geologic mapping and geophysical studies being done as part of the CASCADIA project (CASCADIA Working Group, 1993), seismic reflection (Stanley *et al.*, 1994), gravity and magnetic maps (Finn *et al.*, 1991; Finn, 1995), and MT sounding data (Stanley *et al.*, 1987, 1994) can be combined with seismicity cross sections to study the boundaries and extent of the important crustal blocks in the southern Washington Cascades.

Stanley *et al.* (1994) compiled a geological/geophysical and seismicity cross section (Fig. 5) across the southern Washington Cascade Range (profile AA′, Fig. 3), using well-log and surface geological information combined with industry and Department of Energy (DOE) seismic-reflection and MT data (Stanley *et al.*, 1994). Stanley *et al.* (1992, 1994) interpret that the SHZ (Fig. 5) coincides with the basic crustal contact between the Eocene mafic rocks of Siletzia (Crescent formation) and sedimentary rocks of the SWCC with underlying basement to the east. Although no wells in the basin have penetrated to basement rocks, Crescent formation can be traced on seismic-reflection data from outcrops in the western part of the Chehalis Basin (Stanley *et al.*, 1994; Johnson and Stanley, 1995). The sequence of Oligocene-Miocene volcanic flows of the Ohanapecosh and Stevens Ridge formations (Walsh *et al.*, 1987) in the Cascade Range is interpreted on the cross section to range up to 5-km thick and is underlain by middle to upper Eocene, nonmarine strata of the Puget Group (Stanley *et al.*, 1992, 1994; Fig. 5). The SWCC low-resistivity rocks are nearer the surface in the area of the Skate Mountain anticline, the Carbon River anticline, the Morton anticline, and Bear Canyon (Figs. 3 and 5), where Eocene nonmarine to marginal-marine strata crop out (Stanley *et al.*, 1994; Johnson and Stanley, 1995). To the east, the reflection data suggest a broader extent of the pre-Tertiary basement complex (Fig. 5) that is exposed in the Rimrock inlier (RI, Figs. 1 and 3). The seismic-reflection data also reveal details of basin structure, fold sets, and faults within the SWCC region (Stanley *et al.*, 1994).

As part of the research for this article, we completed two MT profiles, JJ′ and HH′ (Fig. 3), to investigate details of structure across the WRZ and in the Mt. Rainier area. The MT data from profiles JJ′ and HH′ were modeled using a modified version of the two-dimensional inversion program developed by Smith and Booker (1991). The inversion models (Fig. 6) derived after 50 or more iterations were simplified by grouping the model resistivities into four ranges. The MT data are sensitive to features outside the ends of the profiles, and the models are required to extend beyond the actual data spatial limits; therefore, we have shown parts of the model some distance from the ends of the actual data. However, the resolution of the model beyond the actual data decreases rapidly beyond the ends of the profile. For instance, on the model for profile HH′, the western margin of the SWCC is well located because it occurs within the sounding profile; however, the eastern limit of the SWCC beyond the end of the profile data is poorly resolved.

MT models in Fig. 6 show important structures in the Mt. Rainier region. The 1- to 10-ohmmeter units correspond to the SWCC. The western boundary of the conductive rocks on both MT profiles corresponds to the western margin of the Carbon River anticline, but the eastern boundary on profile HH′ is poorly defined because of a lack of MT stations. North of profile HH′, the eastern boundary of the SWCC is near the eastern margin of the Carbon River anticline (Fig. 3; Stanley *et al.*, 1994; Schasse, 1987). Preliminary analysis of an MT profile acquired in 1994 shows that the region just north of Mt. Rainier is composed of high-resistivity rocks inferred to be predominantly Miocene plutons.

On section JJ′ (Fig. 6), the conductive SWCC units dip very steeply beneath Mt. Rainier and appear to merge with a deeper conductive zone on the east end of the profile. The deeper conductive zone may be an extension of the conductive sedimentary units as indicated or analogous to a horizontal, mid-crustal, conductive zone found elsewhere in the Cascade Range (Stanley *et al.*, 1990). Stanley *et al.* (1990) have interpreted this zone to be related to a mid-crustal region of fluids derived from prograde metamorphism caused by high-heat flow. The bottom of the SWCC is not accurately constrained by the MT data on profiles HH′ and JJ′ because at the lowest frequencies measured the conductive complex was not always penetrated. Unpublished lower-frequency soundings completed south of the Mt. Rainier area along the seismic profiles were used to model the thickness shown on the geological/geophysical cross-sectional of Figure 5. The model of profile JJ′ (Fig. 6) is similar in appearance to the MT and seismic models along profile AA′ further south (Fig. 5).

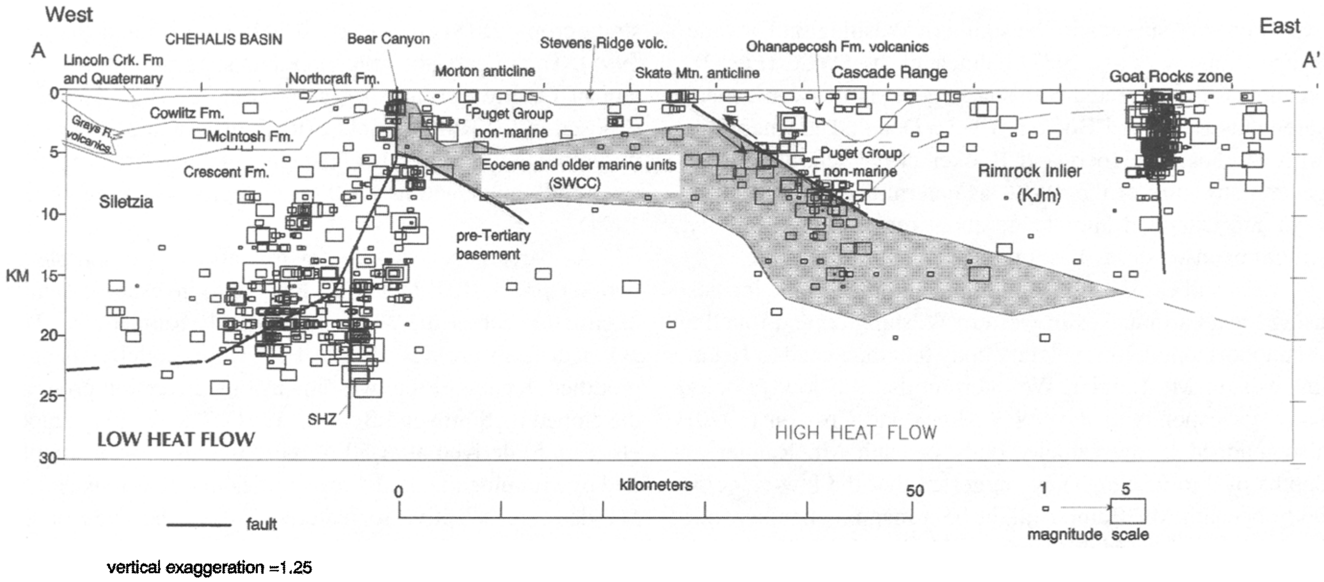


Figure 5. Interpretive cross section along profile AA′ of Figure 3 based upon seismic-reflection data, geological mapping, and MT profiles across the Chehalis Basin-Cascades region (from Stanley *et al.*, 1994). Rectangles are hypocenters (projected normal to profile) from University of Washington catalog (1970 to 1992) for a 0.2° swath centered on AA′. Bold lines are inferred fault zones.

Details of Seismicity in the Southern Washington Cascades

Our analysis of seismicity patterns in the southern Washington Cascades started with the best geophysical/geological cross section available to us, represented in Figure 5, based on detailed gravity/magnetic, seismic reflection, MT, and geologic mapping data. Hypocenters for earthquakes from the University of Washington catalog for 1970 to 1992 in a swath of 0.2° centered on profile AA′ were used to study details of local faults (Fig. 5). Hypocenters were projected onto the section along lines perpendicular to profile AA′. The detailed seismicity plot of Figure 5 reveals that the narrow, vertical zone of seismicity associated with the SHZ slightly to the southeast noted by Weaver and Smith (1983) is not characteristic of the seismicity on profile AA′. Instead, most of the seismicity at the projected location of the SHZ is concentrated at depths of 15 to 25 km in a complex distribution.

Another concentration of hypocenters is located just east of the axis of the Skate Mountain anticline, aligning with an east-dipping thrust fault interpreted from DOE reflection data (Fig. 5). These earthquakes delineate the southern extension of the WRZ (Fig. 1). The upper plate of the thrust fault includes a thick syncline of Ohanapecosh volcanic rocks, Puget Group sedimentary units, and Jurassic-Cretaceous basement (containing probable Miocene intrusions). On the west, the lower plate consists of near-horizontal Puget Group sedimentary rocks, underlain by the thick, east-dipping marine sedimentary complex associated with the SWCC, and underlying basement.

The seismicity concentration in the Goat Rocks area (Figs. 1 and 5) continues northward with poor definition to the region east of Mt. Rainier. The location of this concentration of seismicity on section AA′ is quite evident and most of the earthquakes are shallow, representing mainly right-lateral slip in the basement rocks (focal mechanisms are shown in Fig. 10).

We also analyzed the distribution of seismicity along the detailed MT profiles JJ′ and HH′ across the Carbon River-Skate Mountain anticline and WRZ. We projected seismicity within 0.15° swaths centered on the individual MT profiles onto the models (Fig. 6). A distinct grouping of earthquakes occurs at depths of 2 to 8 km on profile HH′. This grouping occurs in the axis of the Carbon River anticline and may be related to internal faults as discussed earlier; however, the seismicity coincides with interpreted pluton in the MT model (outlined by the bold shaded line). Strain may therefore be concentrated on the margins of the mechanically rigid pluton contained within more compliant sedimentary rocks. Most of the earthquakes projected onto MT section JJ′ were located within the axial part of the Carbon River anticline, suggesting that either strain within the anticline is highest in the axis or that physical conditions and faults within the axis facilitate strain release.

Overall seismicity in the southern Washington Cascade Range region was studied using earthquakes from the University of Washington catalog for the years 1980 to 1994 (Fig. 7). Epicenters of well-located (A or B location quality, as defined in Ludwin *et al.*, 1994) earthquakes from the catalog are plotted in Figure 7 and as horizontal depth slices in Figure 8. The narrow rectangles in Figure 7 indicate swaths

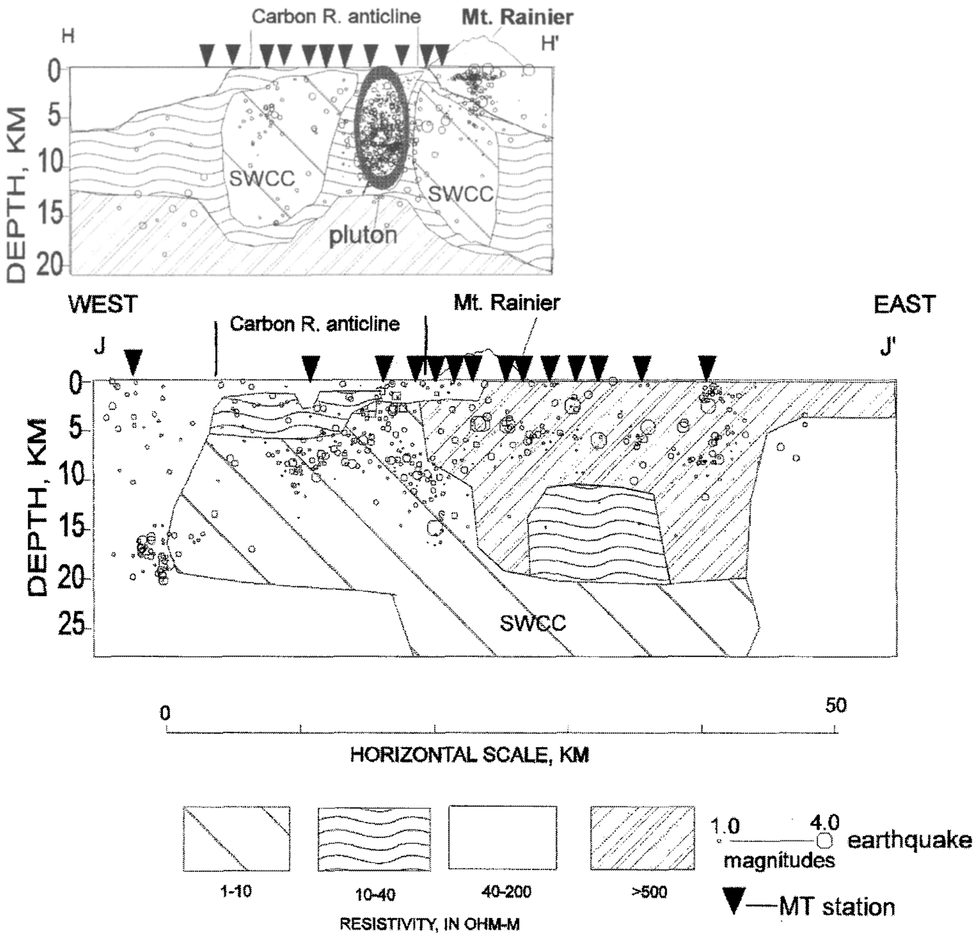


Figure 6. MT models for sounding profiles JJ′ and HH′ with seismic events. Earthquakes within a rectangular 0.15° swath centered on the MT profiles have been projected (projections normal to the swath) onto the models. Patterns denote resistivity ranges for the model sections. The location of Mt. Rainier has been projected onto the two MT cross sections. A resistive zone in the core of the Carbon River anticline on profile HH′ is interpreted to be a Miocene pluton and is highlighted by a gray, bold line, since the pattern for the resistive zone is not visible beneath the seismicity concentration.

for detailed cross sections of seismicity (shown in Fig. 9). Selected focal mechanisms are shown in Figure 10.

Figure 7 reveals dense seismicity along the SHZ and a lower concentration of events associated with the WRZ. The WRZ appears to continue well north of Mt. Rainier. Many earthquakes on the SHZ were associated with fault movement after the 1980 eruption of Mount St. Helens and aftershocks of the M 5.5, 1981 Elk Lake earthquake that occurred 15 km north of Mount St. Helens. The SHZ becomes less distinct north of the Cowlitz River near an east-northeast band of earthquakes evident in the 12- to 20-km-depth range (Fig. 8). The east-northeast concentration of earthquakes may represent a transfer of strain between the SHZ and the WRZ. We refer to such a feature as a stepover after Aydin and Nur (1985) and Biddle and Christie-Blick (1985). Other references use the term overstep in the same context.

The vertical seismicity zonation at depths of about 20 km in Figure 9 (slices X1 to X5) is absent north of the stepover zone (the stepover is in slice X5) between the SHZ and the WRZ. Besides the SHZ to WRZ stepover zone, there also appears to be a northeast-trending seismicity zone that extends southwest from the Portland area to the SHZ. The earthquakes in this zone are concentrated at a mean depth of about 18 km (bold lines on slices X1, X2, and X3; Fig. 9). These earthquakes are apparently related to localized strain in a block of Siletzia basement, which is in contact with the SWCC along the SHZ. Figure 9 indicates that the SHZ is primarily a vertical feature near Mount St. Helens (slice X2) and on the depth slice X1 to the south; however, the SHZ appears to have a steep westward dip on slice X3 (and Fig. 5) and may merge with the concentration of earthquakes at about a depth of 18 km in the lower part of Siletzia.

Seismicity near Mt. Rainier is concentrated southwest and west of the volcano and beneath the summit (Figs. 8 and 9). The small magnitude, shallow earthquakes beneath the summit may be caused by a variety of processes: loading of

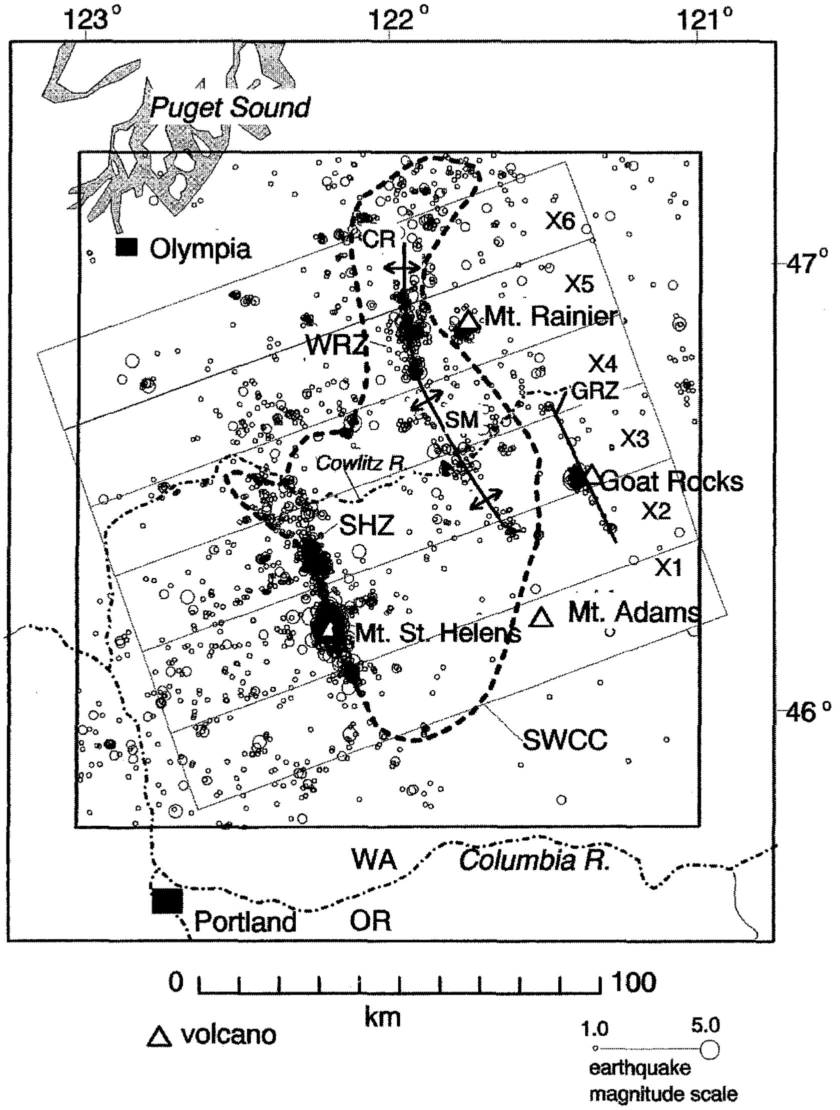


Figure 7. Earthquakes in SWCC study area taken from University of Washington catalog, 1969 to 1994. Bold, dashed line is outline of SWCC. Rectangles are swaths (X1 to X6) used for seismicity cross sections of Figure 9. SHZ = St. Helens zone, WRZ = western Rainier zone; CR = Carbon River anticline; SM = Skate Mountain anticline; GRZ = Goat Rocks zone.

the summit region by ice and volcanic rocks; glacier ice movements; rock, ice, and debris landslides; slip on shallow faults in the volcanic edifice; and hydrothermal or magmatic activity (Weaver and Malone, 1979; Weaver *et al.*, 1990). Although important for geologic hazards assessments, these events are less related to regional tectonics, and we concentrate on the seismic zones west and southwest of the volcano.

The largest concentration of earthquakes in the WRZ occurs along the axis of the Carbon River anticline (Figs. 7 through 9). These earthquakes were located at depths of 2 to 15 km (Fig. 9), placing them within the Puget Group and SWCC assemblage (Figs. 5 and 9). The WRZ was also studied by Thompson (1989), using a magnitude 4.1 event in July 1988 (Fig. 10) and aftershocks. The focal plane solution for the mainshock (Fig. 10) indicates thrusting in a northeast-trending fault. This solution is supported by aftershocks (Thompson, 1989) that were located primarily near a plane that strikes N44°E and dips N72°W. Thus, unlike the SHZ, where focal mechanisms show dominantly dextral strike slip on northwest-trending faults, seismicity on the WRZ shows evidence of fault segments that cross-cut the main strike-slip fault zone. This complexity is also indicated in the geologic mapping by Gard (1968).

There is a grouping of thrust-type focal mechanisms west-southwest of Mt. Rainier (Fig. 10). Seven of the thrust mechanisms indicated in Figure 10 occur either within the stepover zone that connects the SHZ to the WRZ or at the intersection of the stepover with the WRZ. Another four thrust mechanisms are near the north end of the SWCC where another northeast-trending concentration of earthquakes occurred (Fig. 7). It is important to note that the stepovers from the SHZ to the WRZ and at the north end of the WRZ have "releasing bend" geometry in the dextral fault system (Guiraud and Seguret, 1985) and would be expected to be sites of extension, rather than contraction. We provide an explanation for this paradox in the next section.

Seismicity that clusters near a thrust fault under the Skate Mountain anticline outlined in seismic reflection data (Fig. 5) is also shown on cross section X3 (Fig. 9). We infer that the thrust fault was reactivated in a dextral-slip mode

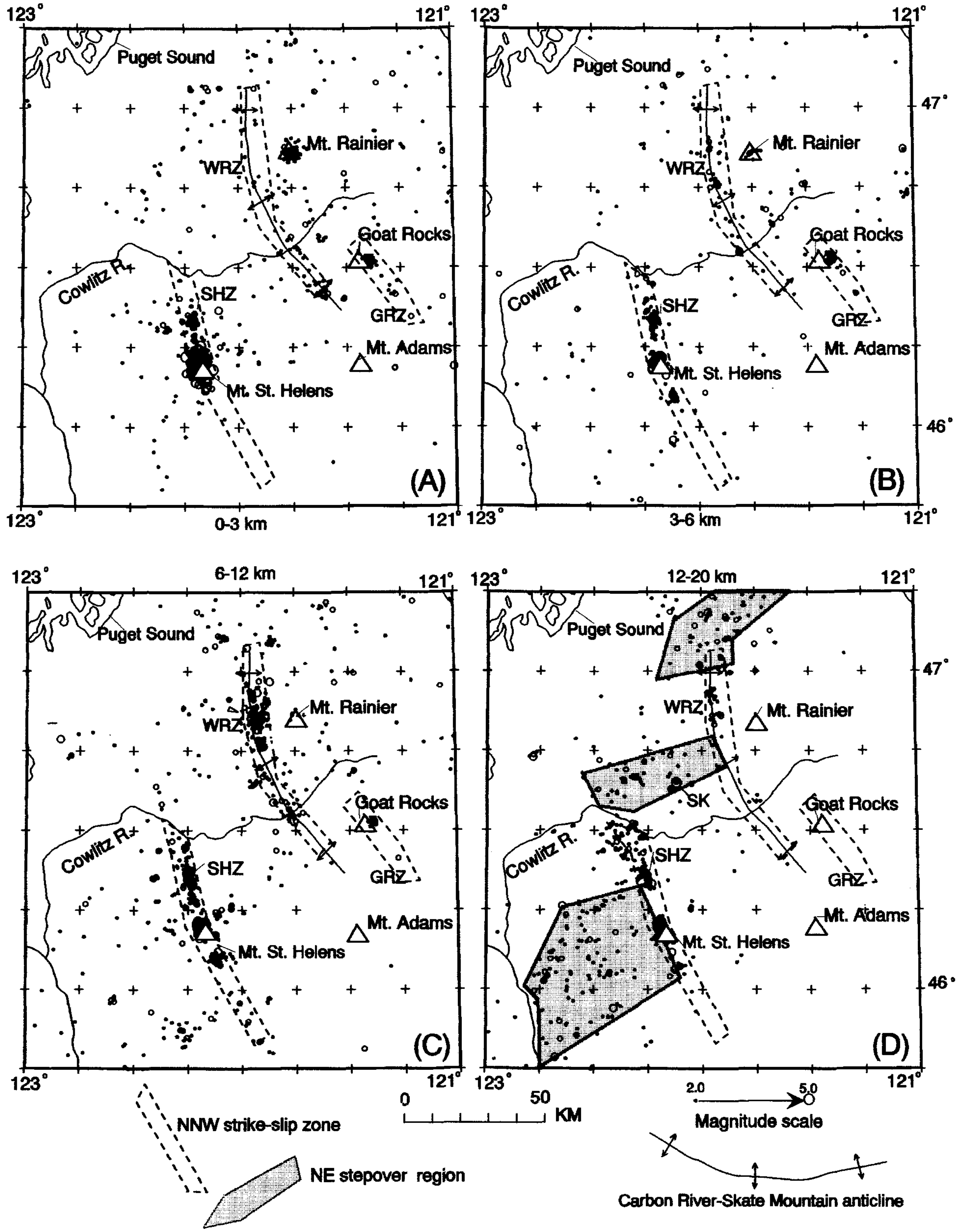


Figure 8. Horizontal depth slices of hypocenters plotted in Figure 7. (a) Slice for 0 to 3 km; (b) 3 to 6 km; (c) 6 to 12 km; (d) 12 to 20 km. SK = Storm King event (on 12- to 20-km slice); GRZ = Goat Rocks zone; SHZ = St. Helens zone; WRZ = western Rainier zone. Stepover zones are indicated by gray boxes and strike-slip zones by dashed outline boxes. Anticlines discussed in text are shown at the same location on all depth slices for reference.

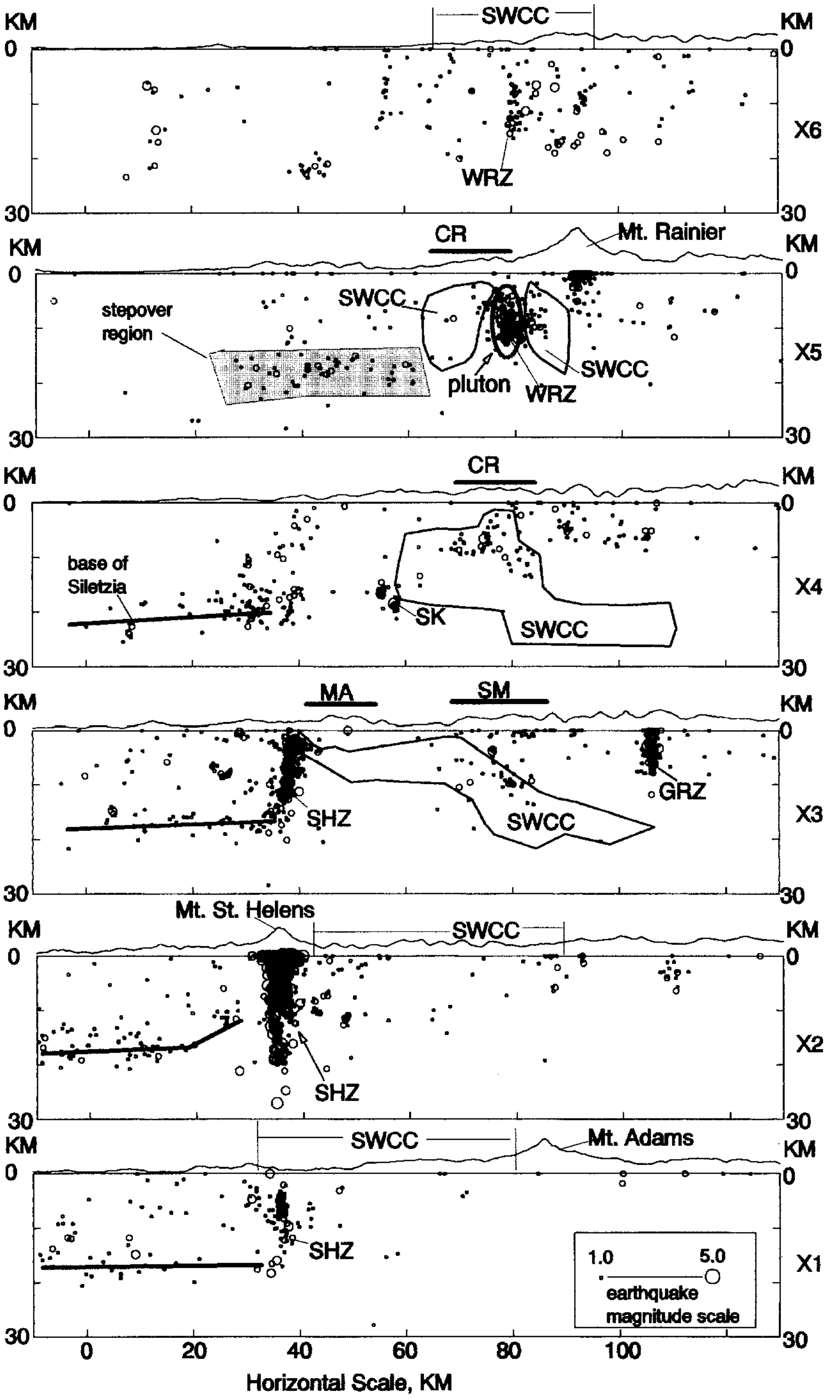


Figure 9. Cross sections of seismicity along swaths X1-X6 of Figure 7. No vertical exaggeration except for topography (2:1). SK = Storm King earthquake; WRZ = Western Rainier zone; SHZ = St. Helens zone; SM = Skate Mountain anticline; CR = Carbon River anticline; GRZ = Goat Rocks zone; MA = Morton anticline. Bold solid lines on west ends of X1 to X4 are interpreted lower surfaces of Siletzia. Simplified interpreted MT cross sections that show the configuration of the SWCC have been projected onto cross sections X3 to X5. The locations of the boundaries of the SWCC on other seismicity cross section as determined from distributed MT soundings are shown by the vertical lines.

and probably continues northward in the area of cross sections X4, X5, and X6 within the WRZ, where it has rotated to a more vertical attitude by increased horizontal contraction to the north. This increased horizontal contraction was interpreted previously by Stanley *et al.* (1992, 1994) from apparent convergence of the Morton anticline with the Carbon River anticline and from increased thickness and reduced horizontal extent of the SWCC complex from south to north (Fig. 9).

A magnitude 4.9 earthquake occurred in 1988 (SK, Fig. 9) with a hypocenter at a depth of 18 km near the stepover zone between the SHZ and WRZ (delineated by events with hypocenters from depths of 12 to 20 Km). The Storm King event had very few aftershocks, and none were greater than magnitude 2.5. The mainshock location (Fig. 9) of the Storm King event shows that it occurred along the margin of the SWCC. The focal mechanism for the Storm King earthquake is consistent with either sinistral slip on an east-dipping, northerly striking fault plane or dextral slip on a north-dipping, east-striking plane (Fig. 10). The spatial distribution of aftershocks for the Storm King event is not adequate to decide which fault plane is appropriate. The compound transpressional model we discuss in the next section favors the east-striking plane.

Tectonic Model for the Southern Washington Cascade Range

Evidence for Transtension and Transpression

Most of the tectonic features of the southern Washington Cascade Range can be related to the effects of Eocene transtension and post-Eocene transpressional deformation. The driving force for Eocene transtension was rapid oblique convergence of Pacific basin plates below western North America (Engebretson *et al.,* 1985). Oblique convergence continued at lower rates from the Oligocene to the present. The transition from transtension to transpression is not easily related to changes in plate convergence vectors and therefore probably reflects the interaction of oblique convergence and continental margin, regional-to-local structure and kinematics. There is abundant evidence in the continental margin from Washington to Alaska for transcurrent deformation (Eisbacher, 1985). Beck *et al.* (1993) have provided an elegant model to explain this type of deformation utilizing the effect of buttressing and subduction zone bending as portrayed in Figure 2. In the analysis of models in this section, we will invoke a local force direction that is small with regard to interior margin domains without requiring the subduction vector to have a small angle to the continental plate.

The Carbon River-Skate Mountain and Morton anticlines provide the most obvious evidence of transpressional deformation but with numerous smaller-scale folds and faults concentrated in and across these features (Walsh *et al.,* 1987). Transpressional deformation is not limited to the region that we discuss in detail in this article, but it is evident in most of southwestern and west-central Washington. The unique characteristics of transpression in the study area are the subject of our models, and we infer that these unique characteristics are largely determined by a very thick, deformable sedimentary section of the SWCC and related boundary conditions.

Transpressional Strain Modeling

Simple transpressional strain models can be useful to illustrate some important elements of expected deformation. First, some assumptions and terms need to be clarified. Most simple mathematical and physical modeling involves homogeneous strain (Fig. 11a), but there is clear indication of inhomogeneous strain in the study area that we deal with in

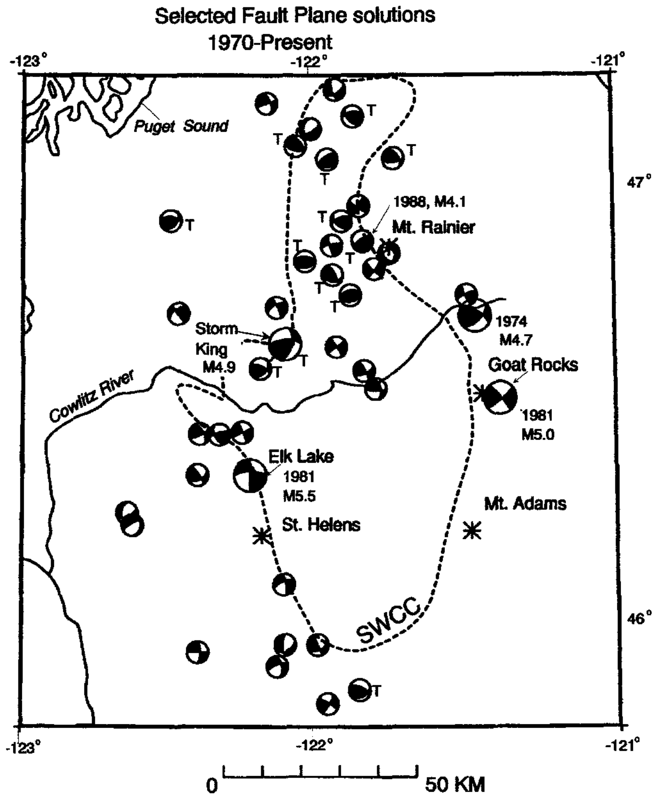
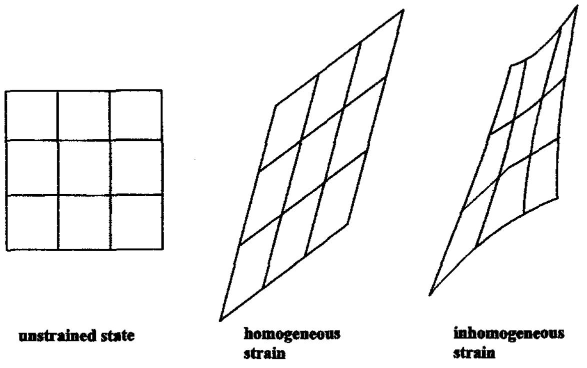
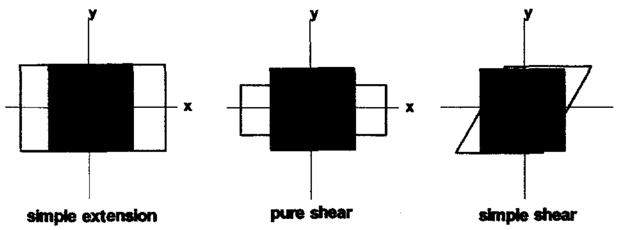


Figure 10. Selected fault plane solutions for earthquakes in the southern Washington Cascade Range. T's signify focal mechanisms of thrust character (B axis plunge less than 45°).



(A) HOMOGENEOUS AND INHOMOGENEOUS STRAIN



(B) FINITE STRAIN IN TWO DIMENSIONS

Figure 11. Explanation of terminology used in the text. Diagrams were modified from Ramsay (1967). (a) Difference between homogeneous and inhomogeneous strain. (b) Distinction between simple extension, pure shear, and simple shear with the light gray box representing the undeformed state, and the open rectangles (and parallelogram) representing the deformed state.

our model of the area. Strain clearly operates in three dimensions in real geology, with lithostatic loading and other forces providing a vertical component. However, most of the transpressive deformation in the study area can be modeled with two-dimensional strain (Fig. 11b). Pure shear and simple shear (Fig. 11b) are definitions of the manner in which specific translations give rise to the state of strain. In our case, we will model the strain effects from the normal and transcurrent forces of oblique subduction.

Two of numerous possibilities for modeling the shears involved in transpression are shown in Figure 12. The dark gray unit cubes represent rigid blocks that experience pure shearing (defined in Fig. 11b) from the normal component of oblique subduction. The light gray unit volume prism represents a deforming zone between the two rigid blocks that undergoes simple shearing (defined in Fig. 11b) from the transcurrent (or wrench) component of oblique subduction (Harland, 1971). Figures 12b and 12c account for changes in the strain ellipsoid under the imposed shears by lateral escape and vertical escape, respectively. For transpression, $a^{-1} < 1$; for transtension, $a^{-1} > 1$; and for classical wrench faulting (Sanderson and Marchini, 1984), $a^{-1} = 1$. In addition to the volume distortion caused by the shearing, other effects are observed at the surface of a physical model (Richard and Cobbold, 1990) or the Earth (Sanderson and Marchini, 1984). These effects typically involve the formation of en-echelon fold and thrust belts and extensional features (extending shears and normal faults) that parallel the directions of minimum and maximum compression (σ_3 and σ_1), respectively. Strike-slip faults also develop or coincide with thrust faults (Sanderson and Marchini, 1984). Harland (1971) demonstrated that the fold-thrust belts form an angle with the simple shear direction but rotate into parallelism as the pure shear strain compresses the deforming zone. The rate at which this occurs is dependent upon the model (or real Earth); in Figure 12b, the approach to parallelism would naturally occur more rapidly than in Figure 12c because of elongation of the fold axes.

The simple models of transpression in Figure 12 illustrate two possible assumptions about boundary conditions, both of which involve constant volume for the deforming zone. Other more realistic assumptions could be made. Tikoff and Teyssier (1994) utilize partitioned displacement, or independent regions within the deforming zone, to model the southern California San Andreas and Great Sumatran faults. When sedimentary rocks are involved in the deforming zone, one could also model the strain using tectonic volume loss (reduction of porosity). Dias and Ribeiro (1994) have demonstrated distortion matrices for the latter and other interesting styles of transpression.

The timing of development of transpressional folding and faulting has been studied with sand box experiments (Richard and Cobbold, 1990; Richard *et al.,* 1991; Pinet and Cobbold, 1992). These experiments indicated early formed folds that tightened and rotated clockwise (for dextral shear), with thrust faults developing within the folds. The folds and faults developed parallel to the direction of minimum compression (σ_3). Thrust faults were subsequently converted to strike-slip faults as contraction continued. The latest-stage features observed were normal faults and shear zones that developed parallel to the direction of maximum compression (σ_1). This pattern of folding and faulting fits the geologic

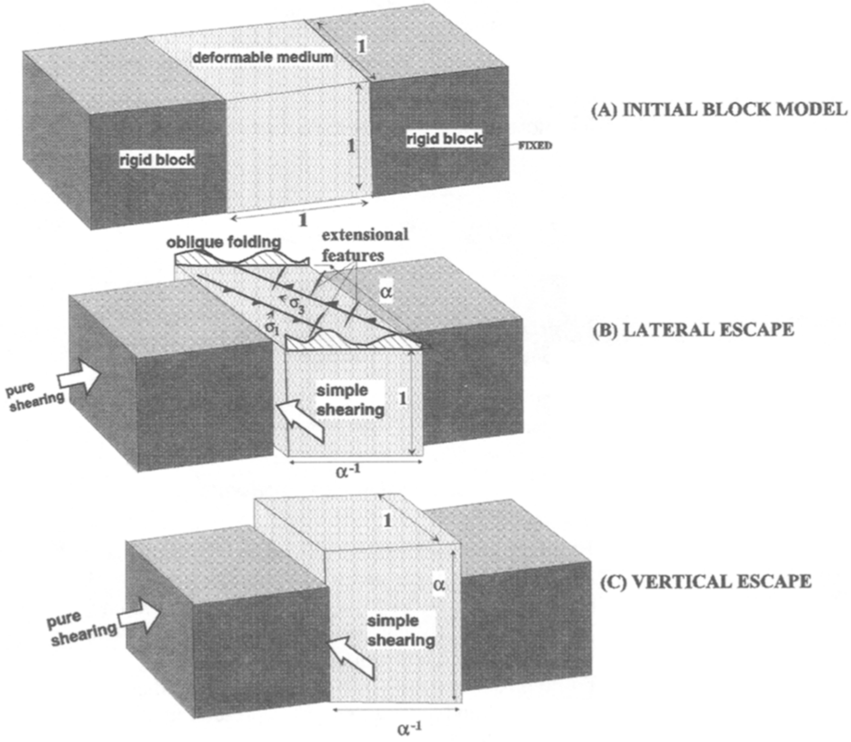


Figure 12. Models for transpression modified from Sanderson and Marchini (1984). (a) Initial model with a unit deformable block (light gray) between two unit rigid blocks (dark gray). The left rigid block undergoes pure shearing, and the deforming block undergoes simple shearing. The second rigid block (dark gray) is fixed or has one-half the shear component of the first block. Diagonal distortion of the unit deforming zone is assumed to be constant volume and can be accommodated by lateral escape (b) or vertical escape (c). The distorted strike length of the unit deformable block is a, and the distorted dip length is a^{-1}. For transpression, $a^{-1} < 1$; for transtension, $a^{-1} > 1$; and for pure shear, $a^{-1} = 1$ (wrenching). Folds, thrusts (sawteeth on hanging wall), and extensional features form, dependent on material properties and boundary conditions. These features are shown superimposed on (b), independent of the lateral escape. Parameters σ_1 and σ_3 are the directions of local maximum and minimum compression.

observations of Gard (1968) in the Carbon River anticline area and our broader observations based on geologic, seismicity, and geophysical data from the SWCC region.

A Compound Transpressional Strain Model

The tectonic features in the southern Washington Cascades are most conveniently explained using a compound transpressional model involving three domains, as shown in Figure 13. Domain 1 represents the mafic blocks of Siletzia to the west of the SWCC and other unknown, rigid crustal components; domain 2 represents the early pull-apart basin complex of the SWCC; and domain 3 represents the pre-Eocene continental margin of the North American plate. When the transcurrent angle, ϕ, was small in early to middle Eocene, the mafic complex of Siletzia may have formed in a near-margin pull-apart system, possibly added by coincidence with a hot spot or leaky transform system (Wells *et al.*, 1984). It is important to note that the transcurrent directions shown are the local force directions and may not correspond to the plate-motion vector azimuth. In Figure 13a, domain 2 may have been bounded to the west by the hypothesized Puget (Johnson, 1984, 1985) fault and to the east by a southern extension of the Straight Creek fault (Fig. 1).

The model (Fig. 13) assumes a free boundary condition at the north ends of domains 1 and 2 during the transtensional episode. The North American plate (domain 3) is fixed in both (A) and (B) stages of the model. In the transpression stage (B), we assume a fixed boundary condition at the north ends of domains 1 and 2. The backstop of pre-Tertiary basement complexes to the north, coupled with a bend in the subduction zone (Fig. 2), is a factor in our assumption of a fixed boundary condition. The fixed boundary is likely a distributed feature of the Puget Lowland; for example, Johnson *et al.* (1994) suggest that thrusting on the Seattle fault (Fig. 1) accommodates much of the northward displacement in the region of domains 1 and 2 in our model.

We interpret that tectonic escape of one or more blocks of domain 1 is required to produce the increased horizontal contraction of the SWCC (domain 2) on the north. This increased horizontal contraction is the largest obvious evidence of inhomogeneous strain (Fig. 11b) in the study area. The increased contraction in the north half of domain 2 in Fig. 13b causes increased clockwise bending of the north

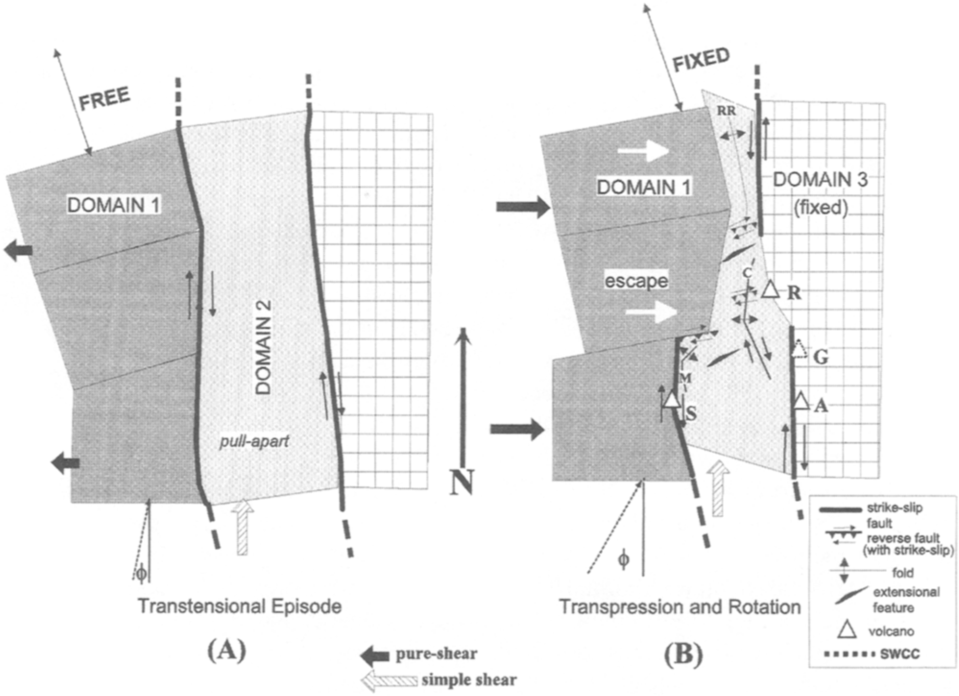


Figure 13. A transtensional-transpressional model developed to explain tectonic features of the southern Washington Cascades. (a) Transtensional stage in which domain 1 (dark gray) is composed of discrete rigid blocks that represent Siletzia and other unknown basement units; domain 2 (light gray) represents a deformable zone assumed to be a pull-apart basin complex; and domain 3 (hatch pattern) is rigid, fixed, and represents the late Cretaceous margin of the North American Plate. (b) Transpressional stage in which tectonic escape is incorporated. The angle between the direction of the total force vector and the continental margin is ϕ. R = Mt. Rainier; G = Goat Rocks (dashed triangle indicates former volcano); A = Mt. Adams, S = Mt. St. Helens; M = Morton anticline; C = Carbon River-Skate Mountain anticlines; RR = Raging River anticline.

ends of the Morton and Carbon River-Skate Mountain anticlines. We also schematically show the approximate location of the Raging River anticline and associated structures in the Black Diamond-Tiger Mountain area (Vine, 1969) to the north of the SWCC where transpressive deformation has occurred (Johnson *et al.,* 1994) but where the thick section of sedimentary rocks in the SWCC does not occur. The lack of this thick sedimentary section may be due to greater basement uplift and erosion in the Black Diamond-Tiger Mountain region.

The escape of blocks of domain 1 may be the primary cause of the stepover in seismicity between the SHZ and the WRZ. The increased horizontal contraction at the north end of domain 2 acts to merge two divergent strike-slip zones of Fig. 13a into the single strike-slip fault zone along the northern domain 2 to 3 boundary in Fig. 13b. Thus, components of strike slip along the western margin of domain 2 are forced to transfer into the interior of the domain, through activation of fold-parallel reverse or thrust faults (in the Carbon River-Skate Mountain anticlines) and in stepovers. We also considered the possible role of interior block rotation in domain 2 as a mechanism for development of this stepover and for the focal mechanism of the Storm King earthquake. Nicholson *et al.* (1986) have demonstrated the role of block rotation between two strike-slip zones in producing stepovers in the southern California San Andreas region. However, most of the evidence appears to us to require the model we present in Fig. 13b, where block rotation of the interior region (domain 2) between the two strike-slip faults is not a factor.

The focal mechanisms of Figure 10 indicate thrust solutions for several events in the stepover region between the SHZ and WRZ and several at the north end of the SWCC (domain 2). These thrust focal mechanisms and a stepover inferred near the north end of the SWCC (Fig. 8d) may be related to the blocking effect of the fixed boundary condition at the north end of domains 1 and 2. With this fixed boundary, there is no way to accommodate northward-directed shear in the northern part of domain 2. The fold-oblique thrust faults shown in domain 2 are shown to agree with the computed east-northeast thrust focal mechanisms (Fig. 10) that occur in the SHZ to WRZ stepover zone and the stepover zone near the north end of the SWCC.

Northeast-trending extensional features (normal faults and shear zones) are indicated in Fig. 13b to honor results from model studies and geologic observations by Gard (1968) for these late-stage tectonic developments. Other effects of late-stage deformation can be observed in divergence of the azimuths of small folds from the azimuths of the main anticlines. Many small folds in the study area trend counterclockwise from the main anticlinal azimuths (Walsh *et al.,* 1987). This is characteristic of the effect of transpression in dextral slip regimes. Sanderson and Marchini (1984) show that the latest-formed folds will honor the incremental strain at the moment of folding, resulting in a pattern of folding with early, major folds at some angle to the margin of the deforming zone and with gentle, minor folds on their shallow-dipping limbs at a higher angle to the margin. They cite field examples from Ireland, Oklahoma, and England for this behavior.

Location of the Main Volcanoes

The locations of Mount St. Helens, Mt. Adams, and Mt. Rainier may be influenced by middle Eocene to present tectonic boundaries schematically shown in the model of Figure 13b. The SWCC (domain 2), an inferred thick section of marine sedimentary rocks, is trapped between basement rocks of the late Cretaceous margin (domain 3) and the accreted mafic complex of Siletzia (domain 1). Mt. Rainier is located on or near the inferred late Cretaceous continental margin. Although the Rimrock inlier is the only surface outcrop constraining the location of the late Cretaceous continental margin in the area (Fig. 3), interpretations of MT and seismic-reflection data (Figs. 5 and 6) can be used to estimate the location more precisely. The deeper, easternmost parts of the SWCC (Figs. 5 and 6) are interpreted to be late Cretaceous to Eocene accretionary sediments that have been thrust beneath the late Cretaceous continental margin. The resistive units overlying the SWCC complex beneath Mr. Rainier on the MT model for profile JJ′ (Fig. 6) may be largely composed of Oligocene-Miocene intrusive rocks, but the steep boundary between highly resistive and more conductive rocks just west of Mt. Rainier is interpreted to be near the western edge of the late Cretaceous margin (domain 3). Mt. Adams and Goat Rocks volcanoes are also located on or near the late Cretaceous continental margin. Mount St. Helens is located on the contact between the Siletzia block (domain 1) and the SWCC sedimentary complex (domain 2). The simplest process that would explain this interpreted location of volcanoes on block boundaries is the enhanced ability of magma to make it to the surface along these actively slipping, weak structural boundaries. Small releasing bends in the slip zones may allow for extension that facilitates the access for magma.

Summary

We have developed a transpressional model to explain important tectonic features of the southern Washington Cascade Range. The model is based on geological information, seismicity patterns, and geophysical data, such as MT, gravity, magnetic, and seismic-reflection surveys. Seismicity in a zone west of Mt. Rainier is concentrated along reactivated reverse faults within the Carbon River-Skate Mountain anticline system that formed in sedimentary rocks of the SWCC and overlying volcanic rocks. Some earthquakes in the WRZ, like those in the July to August 1988 earthquake sequence, are concentrated around inferred inhomogeneities within the SWCC sedimentary assemblage, such as intrusive bodies. Other earthquakes are interpreted to be associated with northeast-trending blind thrusts. Transpression is apparent in the north-northwest-trending fold sets, fold-parallel reverse faults and strike-slip faults, fold-oblique normal and reverse faults, and the apparent compressive convergence of the Morton and Carbon River anticlines. A stepover manifested by seismicity in the 12 to 20-km-depth range connects the SHZ and WRZ, and another appears to be located near the northern part of the Carbon River anticline. A stepover region may also exist between the Portland Hills fault zone in the Portland area and the SHZ. Our compound transpressional model is conceptual in design, but with detailed information on strain rates in the southern Washington Cascades region, a full computational model of this concept could be tested. Physical models may also be useful for further understanding of this complex region.

Details of block structure and appropriate strain models could be utilized to refine estimates of the magnitude of earthquakes likely to be generated in fault zones such as the SHZ and the WRZ. In order to place regional seismicity of the southern Washington Cascade Range in a broader framework, we have outlined several factors that may explain the concentration of earthquakes at depths of 15 to 25 km typical of western Washington.

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