Oblique Strike-Slip Faulting of the Cascadia Submarine Forearc: The Daisy Bank Fault Zone off Central Oregon

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INTRODUCTION

The Cascadia submarine forearc off Oregon and Washington is deformed by numerous active WNW-trending, left-lateral strike-slip faults. The kinematics of this set of sub-parallel left-lateral faults suggests clockwise block rotation of the forearc driven by oblique subduction. One major left-lateral strike-slip fault, the 94 km-long Daisy Bank fault, located off central Oregon, was studied in detail using high-resolution AMS 150 kHz and SeaMARC-1A sidescan sonar, swath bathymetry, multichannel seismic reflection profiles and a submersible. The Daisy Bank fault zone cuts the sediments and basaltic basement of the subducting Juan de Fuca plate, and the overriding North American plate, extending from the abyssal plain to the upper slope-outer shelf region. The Daisy Bank fault, a near-vertical left-lateral fault striking 292°, is a wide structural zone with multiple scarps observed in high-resolution sidescan images. From a submersible, we observe that these scarps offset late Pleistocene gray clay and overlying olive green Holocene mud, dating fault activity as post-12 ka on the upper slope. Vertical separation along individual fault scarps ranges from a few centimeters to 130 meters. Using a retrodeformation technique with multichannel reflection records, we calculate a net slip of 2.2 ± 0.5 km. Fault movement commenced at about 380 ± 50 ka near the western fault tip, based upon an analysis of growth strata and correlation with deep-sea drill hole biostratigraphy. We calculate a slip rate of 5.7 ± 2.0 mm/yr. for the Daisy Bank fault at its western end on the Juan de Fuca plate. The motion of the set of oblique faults, including the Daisy Bank fault, may accommodate a significant portion of the oblique component of plate motion along the central Cascadia margin. We propose a block rotation model by which the seawardmost part of the forearc rotates clockwise and translates northward.


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Fig. 1. Shaded relief bathymetry and topography of the north-central Oregon continental margin, created from NOAA swath bathymetry (BS3 and SeaBeam), shelf contours, and USGS DEM's. Inset shows tectonic setting of Cascadia Subduction Zone (CSZ) and location of DSDP Site 174. Four left-lateral strike-slip faults, including the Daisy Bank fault, are shown. Quaternary and Pliocene structures of the shelf and slope were mapped from seismic reflection profiles, sidescan sonar, and swath bathymetry (Goldfinger et al., 1992a).
In this paper we describe in detail one of these active strike-slip faults, the Daisy Bank fault (DBF), off central Oregon. We map and characterize this active structure, determine its sense of motion and rate of slip, and speculate on its origins and the role of such faults in the deformation of the Cascadia forearc.

**DAISY BANK FAULT**

The Daisy Bank fault [formerly called fault B, Goldfinger et al., 1992] was surveyed along its entire length with SeaMARC-1A 30 kHz sidescan sonar at a 5 km swath width (Figure 2) from the abyssal plain to the continental shelf. On the upper slope, we imaged the fault zone with both SeaMARC-1A 5 km and AMS 150 kHz 1 km sidescan swaths (2.5 m and 0.5 m resolution respectively). The fault zone and surrounding structures were also imaged by SeaBeam swath bathymetry on the abyssal plain and continental slope, and NOAA BS$^3$ shallow-water swath bathymetry over Daisy Bank on the upper slope and outer shelf. We conducted a series of dives using the DELTA submersible in 1992-1993 to ground truth the sonar imagery and investigate the DBF at outcrop scale. The DBF extends 94 km from the abyssal plain (Juan de Fuca plate), across the deformation front and continues across the continental slope landward to the continental shelf (North American plate). It probably terminates against the western edge of the deeply buried basement block of lower Eocene Siletz River Volcanics oceanic basalt [Snavely, 1987; Duncan and Kulm, 1989; Tréhu et al., 1994] which underlies the forearc basins of the continental shelf (Figure 1). The landward terrane, called Siletzia, extends eastward across the Coast Range and Willamette Valley of western Oregon and forms a high-strength backstop for the accretionary wedge. This fault is more prominently expressed on the outer shelf-upper slope (accretionary wedge-forearc basin) than any of the other strike-slip faults in the Cascadia subduction zone.

![Fig. 2](image-url)
Upper Continental Slope and Shelf

Daisy Bank is one of several uplifted Neogene structural highs located on the upper slope to outer shelf off Oregon [Kulm and Fowler, 1974]. The DBF bounds the southern flank of Daisy Bank; a second less prominent strand of the fault bounds the northern flank. SeaMARC-1A sidescan imagery, multichannel (MCS) and single channel (SCS) seismic reflection data show that the Daisy Bank fault is a wide structural zone, within which Daisy Bank is uplifted as a horst between two strands of the main fault (Figure 2). The main fault zone is 5-6 km wide northwest of Daisy Bank, widening around the oblong bank, then narrowing to a single strand to the southeast. Multiple scarps are evident, with variable vertical separation southeast of Daisy Bank (Figure 3). Northwest of the bank, two main strands are evident, both up to the north. The traces of the fault strands are straight, implying a near vertical fault. Sidescan imagery shows reversals of vertical separation along strike, a characteristic common only to strike-slip faults. Probable drag folds of exposed strata, with a left-lateral sense of motion, are visible in sidescan imagery southeast of the bank (Figure 3). Mapping from seismic reflection profiles indicates 2-3 km left lateral offsets of NNW-trending accretionary wedge fold axes at Daisy Bank [Goldfinger et al., 1992a; 1995]. Scarp heights measured from the submersible range from tens of centimeters to 47 m. The net uplift of the southern flank of Daisy Bank by both folding and faulting is about 130 m. The most prominent scarp is a steep (25°-50°) debris-covered slope, the debris typically consisting of a chaotic arrangement of angular gray mudstone blocks on the lower slopes and angular to tabular carbonate-cemented mudstone slabs on the upper slopes.

From the submersible DELTA, we traced one of the Daisy Bank scarps into an area of low relief and mud deposition. We observed a fresh scarp striking 290° across the unconsolidated Holocene mud (Figure 4), which is also visible in the AMS 150 kHz sidescan images (Figure 3B). At the outcrop scale, we observed both right- and left-stepping en echelon fault traces, although left-stepping was dominant. This fresh fault scarp ranges from a few centimeters to 1.0 m in height, dips steeply south with the south side up, and offsets cohesive gray late Pleistocene clay as and the overlying olive-green Holocene mud (Figure 4). This sharp change in color occurs at about 12 ka.
in sediments on the upper slope off Oregon-Washington [Barnard and McManus, 1973], indicating post 12 ka motion on this segment of the Daisy Bank fault. Abrupt vertical changes in oxidation color of the late Pleistocene clay, and corresponding abrupt upward increases in bioturbation by benthic animals inhabiting the scarp face suggest that the scarp may represent multiple Holocene tectonic events.

We observed and mapped spectacular carbonate chimneys, doughnuts, and slabs within 100-150 m of the traces of the DBF. Their occurrence decreases rapidly with distance from the fault. The micritic carbonates precipitate from methane-rich fluids venting from both shallow and deep fault zones within the accretionary prism [Ritger et al., 1987; Kulm and Suess, 1990]. Several investigators have observed a close association between fluid venting, carbonate deposition, and active faulting along the DBF and other active faults in the Cascadia forearc [Ritger et al., 1987; Kulm and Suess, 1990; Sample et al., 1993; Shipboard Scientific Party, 1994].

The main fault scarp southeast of Daisy Bank localizes the largest concentration of carbonate deposits yet found on the Oregon margin. Tabular carbonate blocks cover much of the flat top of Daisy Bank. Near the top of the scarp slope, carbonate-bearing boulders up to 6 m in the longest dimension are common. Near fault zones, we observed tabular bodies 10-30 cm in thickness are a common mode of carbonate occurrence over wide areas of otherwise unconsolidated Holocene sediment. These slabs were broken and disrupted in a pattern similar to a parking lot excavated by a bulldozer. We presume that this pattern of disruption is tectonic in nature. We observed minor breakage of carbonate bodies by bottom-fishing activity, but conclude that this breakage is clearly distinguishable, and could not be responsible for the widespread and pervasive disruption we observed near the DBF.

**Lower Slope**

Using SeaMARC sidescan imagery, we traced the Daisy Bank fault zone across the lower continental slope (Figures 2, 5). The fault morphology is subdued on the lower slope relative to the upper slope or the abyssal plain. The DBF is characterized by discontinuous fault traces that disrupt thrust anticlines, and to a lesser degree, the intervening basins. One 3-4 km long strand terminates at the foot of a thrust ridge, producing gullies and a prominent slump scarp. Farther seaward, several splays of the DBF truncate the frontal thrust anticline of the accretionary wedge (Figure 5). Reversals of vertical separation occur along this ridge, with several tens of meters of relief evident along the main splay. The DBF crosses the boundary between the Juan de Fuca and North American plates in a 1 km-wide fault zone that appears to have localized slumping of the seaward limb of the frontal thrust (Figure 5). The intersection of the DBF and the accretionary wedge marks a transition in structural domains between seaward-vergent thrusts (seaward directed thrusting) to the south and landward-vergent thrusts (landward directed thrusting) to the north [MacKay et al., 1992; MacKay, 1995; Goldfinger et al. 1992]. The vergence transition is complex, and occurs over a 15 km length of the initial thrust ridge. Fifteen kilometers south of the DBF, the vergence direction is entirely seaward. The initial thrust ridge in this region has apparently undergone a progressive vergence reversal from south to north along the margin (6). The transition from seaward to landward is manifested as progressive undercutting of the originally landward vergent ridge by a seaward vergent
thrust that is growing northward. The transition to landward vergence is complete at the intersection of the leading ridge with the DBF, where the undercutting seaward-vergent thrust terminates.

Fig. 5. Perspective view of the Daisy Bank fault zone - accretionary wedge intersection, viewed from the west-southwest. The seafloor is represented by a 5 km-wide SeaMARC sidescan sonar image draped over SeaBeam swath bathymetry. High backscatter areas are light tones in the sidescan image. Multiple fault traces on the first ridge are shown by small white arrows. In the cutaway section, seismic reflection line MCS-37 shows the internal structure of the pressure-ridge anticline. Depth in two-way time (seconds) is shown at left margin. Thrust vergence in the accretionary wedge is landward to the north of the fault zone, and seaward to the south. Kilometer scale is approximate for foreground only.

*Abyssal Plain*

In sidescan images, the DBF crosses the deformation front without interruption (Figure 5), extending 21 km seaward onto the abyssal plain where surface and sub-surface expression die out (Figure 2). The main fault trace intersects a 150 m-high ridge along the boundary between the landward-vergent thrust ramp and the fault. MCS lines 37 (Figure 5) and 19 (not shown) show this ridge to be a southwest-vergent thrust ridge bounded by the DBF on its southern flank. The main strand of the DBF steps to the right at the western end of this anticlinal ridge and continues to the northwest (Figure 5 cutaway). We interpret it as a pressure ridge developed between the two overlapping fault strands. A similar pressure ridge occurs at a right step of the Wecoma fault 34 km to the north (Figure 1; Goldfinger *et al.*, 1992, 1995). Basement reflectors show two offsets, one up-to-the-north and one up-to-the-south, that define a "popup" of the basement across the DBF on MCS line 37. We observe the same vertical
structure across the Wecoma and Alvin Canyon strike-slip faults, also on line 37 (See Plate 1 of MacKay, 1995). The DBF is up to the north in both seismic data and sidescan images, the same vertical separation as observed for the other four strike-slip faults found on the Juan de Fuca plate.

While there are no surficial piercing points from which to determine horizontal offset, we can reconstruct the fault's displacement history from the abyssal plain sedimentary section. To estimate the overall net slip and slip-rate for the Daisy Bank fault on the abyssal plain, we applied a geometric technique for restoration of strike-slip fault motion described by Goldfinger et al. [1992, 1995]. This method utilizes the geometry of trenchward thickening abyssal plain sediment wedges in at least one trench-parallel and at least two trench-normal seismic reflection profiles. This configuration is the minimum required to establish 3D piercing points based on the geometry of abyssal plain sedimentary units. Isopachs in this area trend uniformly north-south in pre-faulting sediments, based on the 1989 MCS survey (line spacing 2-4 km; partial tracks shown in Figure 2). We determined the position in the sedimentary section at which the fault-related growth strata first appears in MCS line 37. We converted the sediment thickness from two-way time to depth using an average velocity of 1680 m/s for Astoria Fan sediments [Goldfinger, 1994].

To determine the net-slip on the fault, we measured the horizontal separation of isopachs in units deposited prior to faulting. This method yields a best fit net slip of 2.2 ± 0.5 km for the Daisy Bank fault on the Juan de Fuca plate. The uncertainty represents the maximum and minimum allowable fault slip that does not produce a severe mismatch of thickness units across the fault. The direction of slip is left-lateral, the same as that shown by the drag folds on the upper slope (Figure 3A). We estimate that faulting began at 380 ± 50 ka, based upon the initiation of fault-related growth sedimentation in seismic records, and correlation with dated strata in DSDP drill hole 174 [see Figure 1 inset for location; Goldfinger, 1994]. This age yields an average slip rate of 5.7 ± 2 mm/yr for the DBF near the deformation front. We assume that the initiation of horizontal and vertical slip were coincident. If this assumption is incorrect, the calculated age is a minimum age. We used the same technique to calculate slip rates for the other strike-slip faults where warranted by data availability [Goldfinger, 1994; McCaffrey and Goldfinger, 1995].
DISCUSSION

Tectonic Model

The DBF and similar oblique strike-slip faults off Oregon and Washington appear to play an important role in the deformation of the marine portion of the Cascadia convergent margin [McCaffrey and Goldfinger, 1995; Goldfinger et al., 1992, 1995]. The set of nine sub-parallel faults with the same sense of slip implies clockwise rotation of forearc blocks about vertical axes of the style first proposed by Freund [1974]. This style of deformation has been proposed for the Oregon and Washington onshore forearc [Wells and Coe, 1985], and for the Aleutian forearc [Geist et al., 1988; Ryan and Scholl, 1993] albeit on a much larger scale. We postulate that these WNW-trending strike-slip faults are R’ Riedel shears within an overall dextral shear couple driven by oblique subduction of the Juan de Fuca plate [Figure 7; Goldfinger et al., 1992]. Several of these transverse strike-slip faults and associated folds cross the Juan de Fuca-North American plate boundary and accretionary prism, extending into the continental shelf basins [Goldfinger et al., 1992, 1995, work in progress]. Paleomagnetically-determined clockwise rotations in coastal basalts in Oregon and Washington suggest that similar processes have operated throughout the Tertiary, with Miocene Columbia River Basalts (12-15 Ma) in western Oregon and Washington rotated 10-30° clockwise [England and Wells, 1991], and Eocene Siletz River Volcanics rotated up to 90° [Wells, 1990], although some of this may be due to microplate rotation and opening of the Basin and Range [Magill et al., 1982]. The location of the axes of rotation (pivot points) of the offshore blocks is presumably at or near their eastern ends, although this is not required. If the pivots are fixed to the North American plate, compression between the blocks is required. We observe evidence of compression across the three central Oregon faults, including the Daisy Bank horst, but not along the Washington faults. Without compression along the block edges, the pivots must translate northward relative to the North American plate. The model shown in Figure 7 suggests areas of compression and extension at the eastern ends of the rotated blocks. Currently we are using new seismic reflection data to test the model by evaluating the late Quaternary depocenters on the Oregon shelf. However, the complexity of this deformation superimposed on the accretionary wedge may preclude a definitive test of the model. This type of model, originally envisioned in a simple shear strike-slip environment, requires an overall dextral shear couple. In a strike-slip environment, we would expect accompanying arc-parallel dextral faulting, for which there is little evidence in Cascadia. However, this model is complicated in that the dextral couple is being driven by an obliquely subducting slab. The mechanics of such a system are poorly known [England and Wells, 1991].

Fig. 7. A - Block rotation model for the central Cascadia forearc. The arc-parallel component of oblique subduction creates a right-lateral shear couple, which is accommodated by WNW-trending left-lateral strike-slip faults. B - Slip on nine mapped WNW-trending left-lateral faults results in clockwise block rotation and northward transport of the forearc. With fixed pivots, compression occurs along the block edges. We infer that Daisy Bank (off central Oregon) has been uplifted by this mechanism.

Fault Origin

What is the origin of the transverse strike-slip faults? Certainly their presence within an active accretionary wedge indicates partitioning of strain into arc-parallel (strike-slip) and arc-normal (thrust) components of oblique convergence. We suggest two classes of origins for the faults: (1) Intraplate stresses within the Juan de
Fuca plate, transmitted across the plate boundary to the North American plate, and (2) Deformation driven by interplate coupling of the subducting and overriding plates. The high-resolution seismic data available for the three central Oregon strike-slip faults shows strong evidence of offset of the basaltic slab for all three of these faults [Appelgate et al., 1992; Goldfinger et al., 1992; MacKay, 1995]. Evidence of slab rupture includes: vertical separation of basement reflectors, some of which do not underlie the surficial structure, and thus could not be velocity pull-up; pop-ups of basement reflectors with fault splays branching upward into the sedimentary section; and abrupt changes in the character of basement reflectors across the Wecoma fault. The style of deformation of two of the Washington faults is virtually identical to the three central Oregon faults, and we suspect that the Oregon faults are analogs for the two Washington faults. The remaining four Cascadia faults show no evidence of surface rupture on the abyssal plain, and thus may be limited to the upper plate, or may not have ruptured that far to the west.

C. Goldfinger et al., [Oblique Strike-Slip Faulting of the Central Cascadia Submarine Forearc, submitted to Journal of Geophysical Research, 1995] calculate that the interplate coupling stress in the Cascadia accretionary wedge is probably insufficient to rupture the subducting slab. Wang et al. [1995], using geodetic data, also infer very low coupling stress on the interplate thrust. We therefore favor an origin involving deformation of the subducting slab that is then partially transmitted into the weaker North American plate. For a fuller discussion of these issues, see C. Goldfinger et al., Oblique Strike-Slip Faulting of the Central Cascadia Submarine Forearc, submitted to Journal of Geophysical Research, 1995. We note a longitudinal pattern of deformation along the DBF and most of the other transverse faults: strong expression on the plain, poor expression on the lower slope, strong expression on the upper slope and outer shelf. This decrease of deformation from the plain to lower slope is also consistent with a lower plate origin. This pattern could result from reduced fault slip across the overpressured and poorly coupled décollement beneath the lower slope. Rejuvenation of the faults on the upper slope is consistent with progressive dewatering of the wedge, and resulting better interplate coupling as would be expected for the rearward part of the wedge. The landward widening fault zones (Figure 1) are also consistent with fault slip transmitted upward through and eastward thickening accretionary wedge.

The observation that the frontal thrust has undergone a progressive vergence reversal, terminating at the DBF, suggests that passage of the DBF beneath the wedge (if the DBF moves NE with the Juan de Fuca plate) may have initiated the vergence reversal. Tobin et al. [1993] suggested that a similar vergence reversal at the intersection of the Wecoma fault and the accretionary wedge is due to fluid pressure loss through the vertical fault. They conclude that a local reduction in pore fluid pressure on the basal décollement results in an increase in basal shear stress, promoting the switch to seaward vergence. While the vergence reversal is probably the result of changes in sediment supply and basal shear stress along the margin [MacKay, 1995], the DBF clearly localizes the vergence change.

Plate Interaction

The observation that five of the nine mapped faults cross the plate boundary is difficult to reconcile with northeasterly subduction at 40 mm/yr [DeMets et al., 1990], since the JDF plate should have traveled 10-24 km to the northeast during the 0.2 to 0.6 Ma elapsed since the initiation of faulting [from 5 faults with known ages; Goldfinger, 1994]. The expected offset due to northeasterly plate motion during this time would be 4-11 km. However, the deformation front also advanced rapidly westward during this period. The DBF (if fixed to the JDF plate) moved about 15 km northeastward since its inception at about 380 ka. This is resolved as 13.2 km normal convergence, and 7.0 km trench parallel motion. We estimate that the westward advance of the deformation front during this period was 8.5-12.7 km, based on microfossil ages of uplifted strata from DSDP site 175 [Kulm, von Huene et al., 1973]. Since the deformation front is constantly renewed by westward advance, the age of its intersection with the DBF is always very young, making any expected offset of the present deformation front minimal.

These factors act to reduce the expected fault offset at the deformation front. However, we conclude that the apparent lack of any measurable offset and the relatively straight trends of the fault zones strongly imply that the lower slope is moving with the subducting plate to some extent. We suggest that the forearc is deforming as a wide shear zone by distributed deformation and translating northward driven by oblique subduction [Pezzopane and Weldon, 1991; McCaffrey and Goldfinger, 1995; England and Wells, 1991]. The exponential arcward die out of clockwise rotations observed in Columbia River Basalt onshore strongly supports a model of distributed deformation driven by the dextral component of oblique subduction [England and Wells, 1991]. The net arc-
parallel rate of deformation estimated from slip rates on the offshore strike-slip faults is sufficient to absorb 50-100% of the oblique component of plate convergence [Goldfinger, 1994; McCaffrey and Goldfinger, 1995]. Similarly, England and Wells, [1991] inferred that the onshore forearc may be absorbing most of the tangential component of oblique convergence, based on the rotation rate of the Columbia River Basalt. Although the mechanics of rotation for Siletzia and for the accretionary wedge are probably different in detail, the general agreement of the two independent datasets supports a model of distributed deformation by dextral shear. We suggest that this process may be occurring in both plates, as indicated by the rupture of the slab by three and possibly five of the transverse faults, and by the presence of faults that are probably limited to the upper plate. Alternatively, the lack of offset could indicate that subduction may have ceased or dramatically slowed within the last 0.5 Ma. Further study is needed to test these hypotheses and shed more light on the complex mechanics of oblique subduction.

Acknowledgments. We thank the crews of the research vessels Thomas Thompson (University of Washington), and support vessels Cavalier and Jolly Roger, pilots of the submersible DELTA, Hiroyuki Tsutsumi, Craig Schneider, Margaret Mumford and members of the Scientific Party on cruises from 1992-1993 during which most of the data were collected. Thanks to Guy Cohrane (UCSC), Mary MacKay and Greg Moore (SOEST) for processing the 1989 MCS data. Multibeam bathymetry data was collected by NOAA and processed by the NOAA Pacific Marine and Environmental Laboratory, Newport OR. Thanks to Chris Fox, and Steve Mutula of NOAA for their assistance with the multibeam data. Thanks to Greg Moore, Ray Wells, and Holly Ryan for helpful reviews. This research was supported by National Science Foundation grants OCE-8812731 and OCE-9216880; U.S.G.S. National Earthquake Hazards Reduction Program awards 14-08-0001-G1800, 1434-93-G-2319, and 1434-93-G-2489, and the NOAA Undersea Research Program at the West Coast National Undersea Research, University of Alaska grants UAF-92-0061 and UAF-93-0035.

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