

Transverse structural trends along the Oregon convergent margin: Implications for Cascadia earthquake potential and crustal rotations

Chris Goldfinger

Department of Geosciences, Oregon State University, Corvallis, Oregon 97331

LaVerne D. Kulm

College of Oceanography, Oregon State University, Corvallis, Oregon 97331

Robert S. Yeats

Department of Geosciences, Oregon State University, Corvallis, Oregon 97331

Bruce Applegate, Mary E. MacKay, Gregory F. Moore

School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii 96822

ABSTRACT

A remarkable set of west-northwest-trending left-lateral strike-slip faults intersects the Cascadia subduction zone. Three of these faults have been mapped off northern and central Oregon by using seismic reflection, SeaMARC-1A sidescan sonar, and SeaBeam bathymetry. These faults are highly oblique to the north-south structural grain of the active accretionary wedge. One of them has 6 km of horizontal slip; the average slip rate is 7–10 mm/yr. The faults cut the subducting Juan de Fuca plate, and can be traced into the North American plate. Folds that deform late Pleistocene and Holocene sediments on the upper continental slope and shelf strike north-northwest to west-northwest. Some of the west-northwest-trending folds are associated with the throughgoing strike-slip faults, whereas other northwest-trending folds are approximately normal to the plate convergence direction. Many of these folds are mapped across the shelf, and several active shelf synclines project toward Oregon's coastal bays, where marsh subsidence events are inferred to be the result of great subduction-zone earthquakes. These subsidence events may actually record the growth of local synclines, possibly as secondary effects of slip on the megathrust. We postulate that shortening of the forearc region by clockwise tectonic rotation, associated with movement of the left-lateral faults and folding of the upper plate, may accommodate a significant amount of plate convergence.

INTRODUCTION

The Cascadia subduction zone off Oregon and Washington should be capable of generating great earthquakes. The convergence rate is fast enough (4.0 cm/yr; DeMets et al., 1990) and the subducting Juan de Fuca plate is young (10 Ma) and buoyant enough to characterize Cascadia as a Chilean-type margin (Heaton and Hartzell, 1987) capable of generating earthquakes with $M > 8.0$. The first geologic evidence for great earthquakes was found in buried marsh deposits of the coastal bays of Washington (Atwater, 1987). Peat layers overlain abruptly by marine sands are perhaps best explained by rapid coseismic submergence accompanied by tsunamis (Atwater, 1987; Darienzo and Peterson, 1990). The absence of historic great earthquakes in Cascadia is explained by long recurrence intervals; the problem is that Cascadia has the lowest incidence of instrumental plate-boundary seismicity of any subduction zone. The unusual lack of seismicity raises the question, Can modern convergence be accommodated by means other than slip on the megathrust? We present new structural data from the Oregon continental margin and subducting Juan de Fuca plate that bear on the response of both

plates to oblique convergence and on the development of repeated coseismic marsh burial deposits along the Oregon and Washington coasts.

ACTIVE TRANSVERSE STRUCTURES OF THE CENTRAL AND NORTHERN OREGON CONTINENTAL MARGIN Abyssal Plain

On the abyssal plain, three west-northwest-trending left-lateral strike-slip faults (A, B, and C in Fig. 1) extend from the abyssal plain across the plate boundary. First discovered in 1986 by SeaMARC 1A sidescan sonar, these faults were imaged extensively in a narrow-swath, high-resolution survey in 1989 (Applegate et al., 1991). In migrated multichannel seismic reflection profiles, all three faults offset the entire 3–4-km-thick sedimentary section, as well as the oceanic basement of the incoming Juan de Fuca plate (MacKay et al., 1991; this study). Magnetic modeling of fault A (Applegate et al., 1991) and reflection profiles both indicate about 75–100 m of vertical separation of the basaltic basement; the northeast block is up. SeaMARC 1A sidescan imagery shows that fault A offsets, in a left lateral sense, a late Pleistocene channel and an older slump scar on the Astoria subma-

rine fan: horizontal displacements are about 120 and 350 m, respectively (Applegate et al., 1991; this study). Isopachs (two-way traveltime) of pre-faulting sedimentary units (AP in Fig. 2) within the abyssal-plain sequence show that these units are offset horizontally 5–6 km by fault A, which represents the net slip on this structure near the deformation front (Goldfinger et al., 1991). Horizontal and vertical displacement on fault A dies to nearly zero 17–20 km seaward of the deformation front. Faults A and B both cut or have generated plunging anticlines near their intersections with the deformation front. The doubly-plunging anticline associated with fault A, 9.3 km seaward of the deformation front, appears to be the result of a compressional right step in the left-lateral fault, and is herein referred to as a pressure ridge (Figs. 1 and 2). Stratigraphic correlations suggest that growth of the pressure ridge was approximately coeval with dip-slip motion on fault A. Stratigraphic thinning over the crest of the pressure ridge and thickening on the downthrown side of the fault are pronounced in the synfaulting section (Fig. 2, upper part of Astoria fan unit AF). Faulting began ca. 600 ± 50 ka, on the basis of the age of strata that separate pre-faulting and

logical communities, fluid flow, and carbonate cementation (Tobin et al., 1991), indicating active faulting. On the initial thrust ridge, a seaward-vergent thrust segment occupies the area between the splays of fault A in an overall landward-vergent thrust setting, which suggests that a local reversal of vergence is induced by the interaction of the thrust and the strike-slip fault. Fault B also coincides with a reversal of thrust vergence at its intersection with the deformation front (MacKay et al., 1991). Faults B and C are also inferred to be left-lateral faults on the basis of offset sediment isopachs in the abyssal plain (Goldfinger et al., 1991). Faults B and C offset the deformation front 3.7 and 2.2 km, respectively, in a left-lateral sense. The active frontal accretionary thrust, however, does not appreciably offset the traces of the strike-slip faults where they cross the plate boundary. These relations suggest that the strike-slip faults may actually be part of the plate boundary, coeval with the frontal accretionary thrusts.

Continental Slope and Shelf

We have correlated three throughgoing, west-northwest-trending, left-lateral strike-slip faults on the lower to upper slope with faults A, B, and C on the abyssal plain (Fig. 1) using GLORIA long-range sidescan, SeaBeam swath bathymetry, and a network of academic and U.S. Geological Survey seismic profiles. At least one of the strike-slip faults (A) on the subducting plate clearly crosses the deformation front into the accretionary wedge. The connection of faults B and C is supported by numerous crossing reflection profiles. Several other west-northwest-trending faults on the slope have, as yet, no documented abyssal-plain extensions. Crossings by individual seismic profiles are augmented by GLORIA imagery and SeaBeam bathymetry, where sigmoidal bending and offset of fold axes and linear west-northwest-trending scarps delimit the orientation of faults observed on reflection profiles (Goldfinger et al., 1991). In northern Oregon, the continental slope consists of upper and lower terraces separated by a major landward-dipping thrust fault and a coincident break in slope (SB in Fig. 1). Seaward of this boundary, thrusts and folds of the accretionary wedge trend north-south, subparallel to the continental margin. Landward of the boundary, folds of the upper slope and shelf, with the exception of outer-shelf submarine banks, trend mostly north-northwest to west-northwest, oblique to the margin. In the structural province traversed by faults A, B, and C, a few of the folds are subparallel to the principal strike-slip faults (Fig. 1). Whereas the genetic relation between these young strike-slip faults and oblique folds is not yet documented, we postulate that they both developed in the regional stress field related to oblique Juan de Fuca subduction. Although many folds on the continental shelf and

upper slope involve older rocks ranging in age from Eocene to Pliocene (Kulm and Fowler, 1974), Pleistocene and Holocene strata are also deformed. Continued activity on older folds and faults on the shelf has resulted in scarps of probable Holocene age on the sea floor, although the continuity of the faults is difficult to document due to absence of sidescan sonar data.

Because the active structures of the inner shelf commonly project into the coast, we postulate that there is related active deformation of the coastal region. We have correlated several offshore faults with onshore structures, notably the Tillamook Bay fault (T in Fig. 1) mapped onshore by Niem and Niem (1985). This structure may have as much as 19 km of left slip in rocks of Miocene age, but the age of movement is still being investigated (R. E. Wells, 1991, personal commun.). Offsets of the uppermost units in a reflection profile 8.5 km offshore show that it is probably active in the nearshore region. Furthermore, active inner-shelf synclines project toward Tillamook, Netarts, Nehalem, Nestucca, Siletz, and Yaquina bays. This relation is similar to that noted in the Coos Bay area of southwestern Oregon (CB in Fig. 1 inset), where South Slough occupies the axis of a late Quaternary syncline that intersects the coast (McInelly and Kelsey, 1990). We propose that, like Coos Bay, many of northern Oregon's bays are influenced by growth of local synclines.

IMPLICATIONS FOR CASCADIA SEISMICITY

The structural features mapped off central and northern Oregon suggest a mechanism for the rapid, periodic submergence of marshes as documented by other investigators in Oregon's coastal bays. Coseismic downwarping along a coastal strip with simultaneous uplift offshore, similar to the vertical response noted by Plafker (1972) for the 1960 $m_w = 9.5$ Chilean and 1964 $m_w = 9.2$ Alaskan events (Heaton and Kanamori, 1984), has been invoked as the mechanism for sudden submergence of coastal salt marshes in Oregon and Washington (Atwater, 1987; Darienzo and Peterson, 1990). However, these two margins differ significantly from the Cascadia margin in that convergence is approximately normal to the margins of Chile and Alaska, whereas convergence is oblique to the Oregon part of the Cascadia margin (DeMets et al., 1990). If active synclines are associated with bays in northern and central Oregon, then growth of local folds may influence or control the burial of marsh surfaces during earthquakes in Oregon. We speculate that both coseismic plate flexure and growth of folds may simultaneously account for the downwarping of the bays, but their relative importance is unknown.

The question remains as to whether the transverse folds and faults described on the slope and shelf are activated in sympathy with movement

on the megathrust, or whether they act independently. The very low seismicity of the upper plate of offshore northern and central Oregon shows that the structures we have mapped are relatively quiescent at present. Independent activity on the structures we have mapped would probably call for a higher incidence of instrumental seismicity than observed, if the convergence rate is accurate. Given the evidence for late Pleistocene to Holocene activity on these faults and folds, and the evidence for large Cascadia earthquakes, their present quiescence circumstantially supports their role as structures secondary to the megathrust.

PLATE COUPLING AND ROTATIONS

Several lines of evidence suggest that the Juan de Fuca and North American plates are well coupled. The strike-slip faults discovered on the subducting plate also cut the overriding North American plate, which strongly suggests coupling between the two plates. We do not know whether the faults originate within the upper or lower plate, or in which direction they propagate. However, the presence of these faults in both plates indicates that interplate shear stress must be high enough at the plate boundary for them to propagate from one plate to the other. The dominant north-northwest- to west-northwest-trending structural grain of the upper slope and shelf also indicates strong plate coupling. The active folds are generally orthogonal to the inferred plate convergence direction and direction of crustal shortening (062° at lat 45° N; DeMets et al., 1990), which suggests that a broad coupled zone extends from the mid-slope region to the vicinity of the coast. The sharp division of structural domains in the mid-continental slope (Fig. 1, SB) may correspond to the seismic front of Byrne et al. (1988). We speculate that seaward of this boundary, basal shear stress is less than that needed to form structures normal to the maximum principal stress (s_1), and that a "backstop" effect at or near the slope break (SB, Fig. 1) dominates the margin-parallel orientation of the youngest structures. Landward of this boundary, folds that are oblique to the continental margin but close to normal to the inferred plate-convergence direction dominate structural orientations, suggesting strong coupling eastward to the coastal region.

A set of parallel strike-slip faults of the same sense of motion requires that the intervening segments and the faults themselves must rotate with time (Freund, 1974). Such rotations are documented for the Transverse Ranges of southern California (Jackson and Molnar, 1990), and for the Oregon and Washington Coast Ranges (Wells and Coe, 1985) on the basis of paleomagnetism. Wells and Heller (1988) reported clockwise rotations of 16° – 22° in 12–15 Ma Columbia River Basalt at coastal sites in western Oregon and Washington. They attributed these

rotations to dextral shear distributed across the forearc region, and a monotonic westward increase in rotation. We speculate that the left-lateral faults we have mapped may be R' (secondary) shears within an overall dextral shear couple driven by oblique convergence, similar to the model proposed by Wells and Coe (1985) for southwestern Washington (Fig. 3) and to a block rotation model proposed by Geist et al. (1988) for the Aleutian Ridge. If this model is correct, upper-plate shortening due to growth of the submarine fold belt and clockwise rotation may account for a significant part of convergence between the Juan de Fuca and North American plates. Some additional shortening due to a thrust component on these transverse faults may also occur. If this is the case, nonelastic deformation of the upper plate may be a significant process acting to absorb some of the plate convergence, and thus the rate of accumulation of elastic strain energy. At present, quantitative data are insufficient to calculate rotation rates and shortening due to these mechanisms, but additional marine field studies of these transverse structures should shed new light on the problem of very low plate-boundary seismicity in Cascadia.

CONCLUSIONS

Three left-lateral strike-slip faults in the Cascadia subduction zone that offset both the Juan de Fuca and North American plates, as well as folds in the upper continental slope and shelf, have a trend that is oblique to the continental margin. These transverse structures suggest that the two plates are well coupled. Furthermore, a considerable amount of plate convergence may be accommodated by folding and clockwise rotation of the forearc region in northern and central Oregon.

We propose that Holocene subsidence events in the Oregon-Washington coastal bays are, at

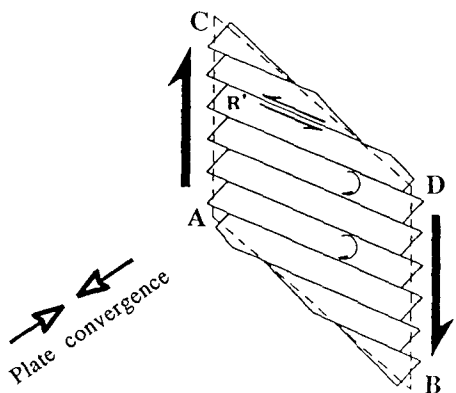


Figure 3. Development of left-lateral R' faults within dextral setting driven by oblique plate convergence. As clockwise rotation occurs, line perpendicular to sites A-B and C-D of parallelogram shortens in direction of plate convergence. After Wells and Coe (1985).

least in part, a response to the growth of active synclines that have trends that are oblique to the coastline. This style of deformation does not support either arguments for great earthquakes or earthquakes of more moderate magnitude. It does, however, offer an alternative mechanism for the sudden submergence of salt marshes that does not require a great earthquake. Nevertheless, we suspect that growth of these structures is triggered by movement on the megathrust because of their low modern seismicity and because geodetic evidence suggests that elastic-strain accumulation and uplift on the adjacent coast are occurring at the same time.

REFERENCES CITED

- Appelgate, B., Goldfinger, C., Kulm, L.D., Mackay, M., Fox, C.G., Embley, R.W., and Meis, P.J., 1991, A left-lateral strike-slip fault seaward of the central Oregon convergent margin: *Tectonics*, v. 10.
- Atwater, B.F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: *Science*, v. 236, p. 942-944.
- Byrne, D.E., Davis, D.M., and Sykes, L.R., 1988, Loci and maximum size of thrust earthquakes and the mechanics of the shallow region of subduction zones: *Tectonics*, v. 7, p. 833-857.
- Darjzeno, M.E., and Peterson, C.D., 1990, Episodic tectonic subsidence of late Holocene salt marshes, northern Oregon central Cascadia margin: *Tectonics*, v. 9, p. 1-22.
- DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990, Current plate motions: *Geophysical Journal International*, v. 101, p. 425-478.
- Freund, R., 1974, Kinematics of transform and transcurent faults: *Tectonophysics*, v. 21, p. 93-134.
- Geist, E.L., Childs, J.R., and Scholl, D.W., 1988, The origin of summit basins of the Aleutian Ridge: Implications for block rotation of an arc massif: *Tectonics*, v. 7, p. 327-341.
- Goldfinger, C., Kulm, L.D., Yeats, R.S., Appelgate, T.B., Cochrane, G., and MacKay, M.E., 1991, Active strike-slip faulting and folding of the Cascadia plate boundary and forearc in northern and central Oregon, in Rogers, A.M., et al., eds., Assessing and reducing earthquake hazards in the Pacific Northwest: U.S. Geological Survey Professional Paper 1560.
- Heaton, T.H., and Hartzell, S.H., 1987, Earthquake hazards on the Cascadia subduction zone: *Nature*, v. 236, p. 162-168.
- Heaton, T.H., and Kanamori, H., 1984, Seismic potential associated with subduction in the northwestern United States: *Seismological Society of America Bulletin*, v. 74, p. 933-941.
- Jackson, J., and Molnar, P., 1990, Active faulting and block rotations in the western Transverse Ranges, California: *Journal of Geophysical Research*, v. 95, p. 22,073-22,087.
- Kulm, L.D., and Fowler, G.A., 1974, Oregon continental margin structure and stratigraphy: A test of the imbricate thrust model, in Burke, C.A., and Drake, C.L., eds., *The geology of continental margins*: New York, Springer-Verlag, p. 261-284.
- Kulm, L.D., Von Huene, R., and Scientific Party, 1973, Initial reports of the Deep Sea Drilling Project, Volume 18: Washington, D.C., U.S. Government Printing Office, p. 97-168.
- MacKay, M.E., Moore, G.F., Cochrane, G.R., Moore, J.C., and Kulm, L.D., 1991, Landward vergence and oblique structural trends in the Oregon margin accretionary prism: Implications and effects on fluid flow: *Earth and Planetary Science Letters*.
- McInelly, G.W., and Kelsey, H.M., 1990, Late Quaternary deformation in the Cape Arago-Bandon region of coastal Oregon as deduced from wave-cut platforms: *Journal of Geophysical Research*, v. 95, p. 6699-6713.
- Niem, A.R., and Niem, W.A., 1985, Oil and gas investigations of the Astoria Basin, Clatsop and northernmost Tillamook counties, northwestern Oregon: Oregon Department of Geology and Mineral Industries Oil and Gas Investigation 14, scale 1:250,000.
- Plafker, G., 1972, Alaskan earthquake of 1964 and Chilean earthquake of 1960: Implications for arc tectonics: *Journal of Geophysical Research*, v. 77, p. 901-925.
- Tobin, H.J., Moore, J.C., MacKay, M.E., Cochrane, G.R., Orange, D.L., Moore, G.F., and Kulm, L.D., 1991, Generation of fracture permeability along a vertical fault at the Oregon accretionary margin and implications for wedge thrust vergence: *Geological Society of America Abstracts with Programs*, v. 23, no. 5, p. A366.
- Wells, R.E., and Coe, R.S., 1985, Paleomagnetism and geology of Eocene volcanic rocks of southwest Washington; implications for mechanisms of tectonic rotation: *Journal of Geophysical Research*, v. 90, p. 1925-1947.
- Wells, R.E., and Heller, P., 1988, The relative contribution of accretion, shear, and extension to Cenozoic tectonic rotation in the Pacific Northwest: *Geological Society of America Bulletin*, v. 100, p. 325-338.

ACKNOWLEDGMENTS

Supported by National Science Foundation Grants OCE-8812731 and OCE-8821577 and by the National Earthquake Hazards Reduction Program, U.S. Geological Survey, Department of Interior, Award 14-08-001-G1800.

Manuscript received August 1, 1991
Revised manuscript received October 21, 1991
Manuscript accepted October 30, 1991

Reviewers' comments

Interesting linkage between coastal geomorphology and active structure of the accreting wedge, and provocative ideas on the nature of plate coupling.

Paul Heller

Important in the continuing controversy about the seismic potential of the Cascadia subduction zone.

Kerry Sieh