UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Earthquake Hazards in the Pacific Northwest of the United States

Compiled by
A. M. Rogers
T.J. Walsh
W.J. Kockelman
G.R. Priest

CENOZOIC EVOLUTION OF THE CONTINENTAL MARGIN OF OREGON AND WASHINGTON

BY PARKE D. SNAVELY, JR[1] AND RAY E. WELLS[1]

Open-File Report 91-441-B

[1]USGS, Menlo Park, California

1991

Foreword

This paper is one of a series dealing with earthquake hazards of the Pacific Northwest, primarily in western Oregon and western Washington. This research represents the efforts of U.S. Geological Survey, university, and industry scientists in response to the Survey initiatives under the National Earthquake Hazards Reduction Program. Subject to Director's approval, these papers will appear collectively as U.S. Geological Survey Professional Paper 1560, tentatively titled "Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest." The U.S. Geological Survey Open-File series will serve as a preprint for the Professional Paper chapters that the editors and authors believe require early release. A single Open-File will also be published that includes only the abstracts of those papers not included in the pre-release. The papers to be included in the Professional Paper are:

Introduction

Rogers, A.M., Walsh, T.J., Kockelman, W.J., and Priest, G.R., "Earthquake hazards in the Pacific Northwest: An overview

Tectonic Setting

Paleoseismicity

Adams, John, "Great earthquakes recorded by turbidites off the Oregon-Washington margin"

Atwater, B.F., "Coastal evidence for great earthquakes in western Washington"

Nelson, A.R., and Personius, S. F., "The potential for great earthquakes in Oregon and Washington: An overview of recent coastal geologic studies and their bearing on segmentation of Holocene ruptures, central Cascadia subduction zone"

Peterson, C. D., and Darienzo, M. E., "Discrimination of climatic, oceanic, and tectonic forcing of marsh burial events from Alsea Bay, Oregon, U.S.A."

Tectonics/Geophysics

Goldfinger, C., Kulm, L.D., Yeats, R.S., Appelgate, B., MacKay, M., and Cochrane, G., "Active strike-slip faulting and folding in the Cascadia plate boundary and forearc, in central and northern Oregon"

Ma, Li, Crosson, R.S., and Ludwin, R.S., "Focal mechanisms of western Washington earthquakes and their relationship to regional tectonic stress"

Snavely, P. D., Jr., and Wells, R.E., "Cenozoic evolution of the continental margin of Oregon and Washington"

Weaver, C. S., and Shedlock, K. M., "Estimates of seismic source regions from considerations of the earthquake distribution and regional tectonics"

Yeats, R.S., Graven, E.P., Werner, K.S., Goldfinger, C., and Popowski, T.A., "Tectonic setting of the Willamette Valley, Oregon"

Earthquake Hazards

Ground Motion Prediction

Cohee, B.P., Sommerville, P.G., and Abrahamson, N.A., "Ground motions from simulated M_W=8 Cascadia earthquakes"

King, K.W., Carver, D.L., Williams, R.A., and Worley, D.M., "Site response studies in west and south Seattle, Washington"

Madin, I. P., "Earthquake-hazard geology maps of the Portland metropolitan area, Oregon"

Silva, W.J., Wong, I.G., and Darragh, R.B., "Engineering characterization of strong ground motions with applications to the Pacific Northwest"

Ground Failure

Chleborad, A. F., and Schuster, R. L., "Earthquake-induced ground failure associated with the April 13, 1949, and April 29, 1963, Puget Sound area, Washington, earthquakes"

Grant, W. P., Perkins, W. J., and Youd, L., "Liquefaction susceptibility maps for Seattle, Washington North and South Quadrangles

Earthquake Risk Assessment

Wang, Leon R.L., Wang, Joyce C.C., and Ishibashi, Isao, "GIS applications in seismic loss estimation model for Portland, Oregon water and sewer systems"

Implementation

Kockelman, W. J., "Techniques for reducing earthquake hazards--An introduction"

Booth, D.B., and Bethel, J.P., "Approaches for seismic hazard mitigation by local governments--An example from King County, Washington"

May, P.J., "Earthquake risk reduction prospects for the Puget Sound and Portland Areas"

Perkins, J.B., and Moy, K.K., "Liability for earthquake hazards or losses and its impacts on Washington's cities and counties"

Preuss, Jane, and Hebenstreit, G. T., "Integrated hazard assessment for a coastal community: Grays Harbor"

Contents

Illustrations

List of Tables

ABSTRACT

The Cenozoic tectonic and depositional history of the Oregon and Washington continental margin (OWCM) was marked by underthrusting, transcurrent faulting, and extension during oblique convergence between North America and oceanic plates to the west. Sedimentation, punctuated by episodes of volcanism, was essentially continuous in the forearc basin whose axis lay along the present inner continental shelf. The oldest rocks in the Oregon-Washington Coast Ranges are Paleocene and lower Eocene oceanic basalt capped in places by islands and seamounts. They most likely formed by in situ eruptions (62-56 Ma) during oblique rifting and extension of the continental margin. These basalts were erupted adjacent to the continental margin as evidenced by locally interbedded terrestrial sediments. A thick lower Eocene siltstone and middle Eocene turbidite sequence buried the islands while the basin was subsiding. The middle Eocene turbidite strata overlap both oceanic basalt and pre-Tertiary rocks of the Klamath Mountains, establishing that suturing of the Coast Range-Olympic terrane to North America occurred at about 50 Ma. Continued high rates of moderately oblique convergence may have caused strike-slip faulting and tectonic rotations along the continental margin. The north-trending Fulmar fault on the Oregon shelf juxtaposes lower Eocene graywacke on the west against lower Eocene oceanic crust of the Coast Range and is interpreted as a right-lateral fault with a minimum offset of 200 km (125 mi). Eruption of upper middle and upper Eocene tholeiitic and alkalic basalts suggests a transtensional tectonic environment inboard of the fault. Reduction of the convergence velocity between the Farallon and North American plates after 49 Ma was followed by Cascade arc volcanism (~44 Ma), and ultimately, the demise of the right-lateral Fulmar fault, as recorded by the onlap of uppermost Eocene strata. Deposition of Oligocene tuffaceous marine strata in the forearc signaled the beginning of voluminous Cascade arc volcanism at about 35 Ma and contemporaneous subsidence of the forearc. Although rift volcanism characterized the forearc during the late Eocene and early Oligocene, there is evidence for late Eocene underthrusting in the Olympic Mountains accretionary wedge. Major uplift of the OWCM occurred in the late middle Miocene as indicated by a regional unconformity on the continental shelf and by strongly deformed Miocene Astoria Formation and the Columbia River Basalt Group in the Coast Range. Offshore, Oligocene-Miocene melange wedges are overlain by as much as 2 km (6,560 ft) of upper Miocene and Pliocene strata which are folded and thrust-faulted. Oblique convergence continues today and has caused Quaternary strata to be episodically folded and thrusted along the deformation front on the continental slope. Along the coast, marine terraces have been tilted during uplift of the central and southern Oregon Coast Range. At the strandline, Holocene marsh deposits record several episodes of rapid subsidence possibly related to seismic events on the thrust interface with the downgoing slab. Late Cenozoic faults along the coast are adjacent to subsiding regions, and some of these faults show Quaternary displacement.

INTRODUCTION

Sedimentary and volcanic rocks in the Coast Ranges of Oregon and Washington, in the Olympic Mountains, and on the adjacent continental margin contain a nearly continuous record of Cenozoic sedimentation and tectonism along the oblique convergent margin between the oceanic and North American plates. Although subduction has played a major part in the evolution of the convergent margin, the geologic record indicates a complex history that includes strike-slip faulting, block rotation, extension, and magmatism, along with typical convergent margin processes of thrusting, underplating, and development of a major accretionary wedge. In this paper, we summarize the onshore and offshore Cenozoic geologic framework of the continental margin, building on previous syntheses by Snavely (1987) and Wells and others (1984). We emphasize the geologic history, regional structure, and offshore evidence for neotectonics to set the stage for evaluation of earthquake potential along this active margin.

CENOZOIC GEOLOGIC HISTORY

PALEOCENE TO MIDDLE EOCENE

ORIGIN OF THE COAST RANGE OCEANIC BASEMENT

The oldest rocks of the Oregon and Washington Coast Ranges are tholeiitic pillow basalt and interbedded breccia and marine sedimentary rocks (fig. 1; Duncan, 1982; Bukry and Snavely, 1988). These oceanic basalts, capped in places by islands and seamounts, include the Siletz River Volcanics in Oregon (Snavely and others, 1968), the Crescent Formation in Washington (Arnold, 1906; Brown and others, 1960; Cady, 1975) and the Metchosin Volcanics on southern Vancouver Island (Clapp, 1917; Muller, 1977). Although several models have been proposed for the origin of these basalts (for example, Duncan, 1982; Wells and others, 1984), we prefer the model of rifting and in situ volcanism along the leading edge of the continental margin of western North America during a period of rapid, highly oblique, northeast motion of the Kula and Farallon plates that was initiated in the Paleocene (fig. 2; Wells and others, 1984; Snavely, 1987).

The western boundary of the Coast Range oceanic basement is a north-south-trending fault on the Oregon continental shelf that has been delineated by aeromagnetic data, seismic-reflection, and deep test wells (table 1). This fault was named the Fulmar fault by Snavely and others (1980b) and is interpreted to have at least 200 km of dextral slip motion, based on the juxtaposition of lower Eocene turbidite sandstone outboard of the Coast Range oceanic basement.

The Fulmar fault is believed to be the western boundary of the oblique marginal rift basin that is floored by the Paleocene-lower Eocene tholeiitic pillow basalt. Along with other dextral faults farther to the east it formed a transtensional zone of right-lateral shear along the Eocene continental margin of Oregon and western Washington. The major movement along the Fulmar fault most likely ended by late Eocene time, because on the Oregon shelf this fault is overlapped by strata of latest Eocene age (~37 Ma) (Snavely and others, 1980b). However, minor movement has occurred subsequently as overlying strata as young as Pleistocene exhibit small vertical offsets on seismic-reflection profiles.

BASIN FILLING AND DEFORMATION

Within the rift basin, a 3,000 m (9,840 ft) sequence of siltstone, turbidite sandstone, and conglomerate of early Eocene age was deposited adjacent to the volcanic highs. The

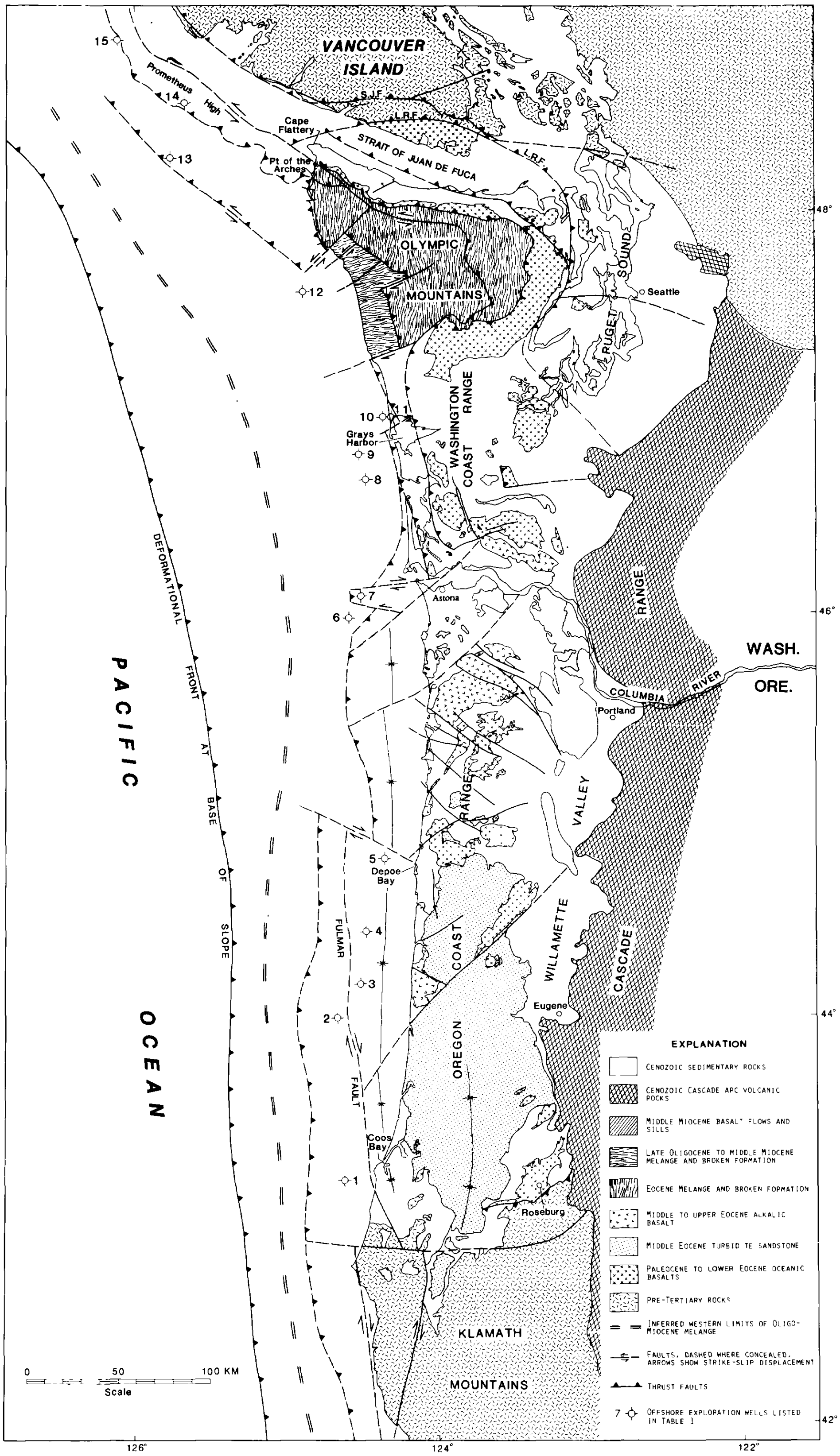

Figure 1. Generalized onshore geologic map of western Oregon, western Washington, and southern Vancouver Island, B.C., with inferred locations of major faults on the adjacent continental shelf. Offshore faults concealed by younger strata are indicated by short dashes. Modified from Snavely (1987). LRF, Leech River fault; SJF, San Juan fault. Outcrops of middle Miocene basalt not shown in Willamette Valley; upper middle Eocene volcanics not shown in eastern part of Puget Sound.

Table 1. Location, depths, and oldest rock penetrated in exploratory wells drilled on the Oregon and Washington continental shelf and selected wells drilled on the shelf off southern Vancouver Island, British Columbia.

Well Number (Fig. 1)	Company, Name, and Number of Well	Year Drilled	Location Latitude (North)	Location Longitude (West)	Total Depth m (ft)	Oldest rocks penetrated
1	Pan American Oil Co. No. 1, P-0112	1967	43°4.8'	124°35.6'	1,873 (6,146)	Lower Eocene arkosic wacke (Snavely and others, 1982)
2	Union Oil Co. Fulmar P-0130	1966	44°03.6'	124°38.8'	3,744 (12,285)	Lower Eocene arkosic wacke (Snavely and others, 1982)
3	Shell Oil Co. P-087 1ET-2ET	1965	44°13.3'	124°28.2'	2,546 (8,353)	Lower(?) Eocene basalt (Snavely and others, 1982)
4	Union Oil Co. Grebe P-093	1966	44°29.8'	124°24.9'	3,051 (10,010)	Lower(?) Eocene basalt (Snavely and others, 1982)
5	Standard Oil Co. Nautilus No. 1 PO-0103	1965	44°51.5'	124°16.7'	3,849 (12,628)	Middle to upper Eocene basalt(?) (Snavely and others, 1982)
6	Shell Oil Co. P-072 1ET	1966	46°02.8'	124°29.9'	2,505 (8,219)	Upper Oligocene to middle Miocene melange(?)
7	Shell Oil Co. P-075 1ET	1966	46°09.1'	124°24.5'	3,097 (10,160)	Middle(?) Eocene diabase sill
8	Shell and Pan American Oil Co. P-0150	1966	46°43.5'	124°21.3'	4,017 (13,179)	Upper Oligocene to lower Miocene melange and broken formation
9	Shell Oil Co. P-0155 1ET	1967	46°51.2	124°24.5'	3,402 (11,162)	Upper Oligocene melange (Snavely and Wagner, 1982)
10	Union Oil Co. Tidelands State No. 2	1962	47°03.22'	124°12.81'	1,546 (5,073)	Lower to middle Miocene melange and broken formation
11	Sunshine Mining Co. Medina No. 1	1962	47°03.03'	124°10.02'	1,262 (4,140)	Lower Miocene melange (onshore well produced 12,000 bbls of oil)
12	Pan American Oil Co. P-0141	1967	47°39.7'	124°47.5'	3,160 (10,368)	Middle to upper Eocene melange (Snavely and Kvenvolden, 1989)
13	Shell Canada Ltd. Anglo Cygnet J-100	1969	48°19.67'	125°43.96'	2,460 (8,070)	Lower to middle Miocene (Snavely and Wagner, 1981; Shouldice, 1971)
14	Shell Canada Ltd. Anglo Prometheus H-68	1967	48°48.9'	125°39.6'	2,335 (7,662)	Lower(?) Eocene Crescent Formation (Shouldice, 1971)
15	Shell Canada Ltd. Anglo Zeus I-65	1868	48°54.6'	126°09.15'	3,042 (9,981)	Lower(?) Eocene arkosic wacke (Shouldice, 1971)

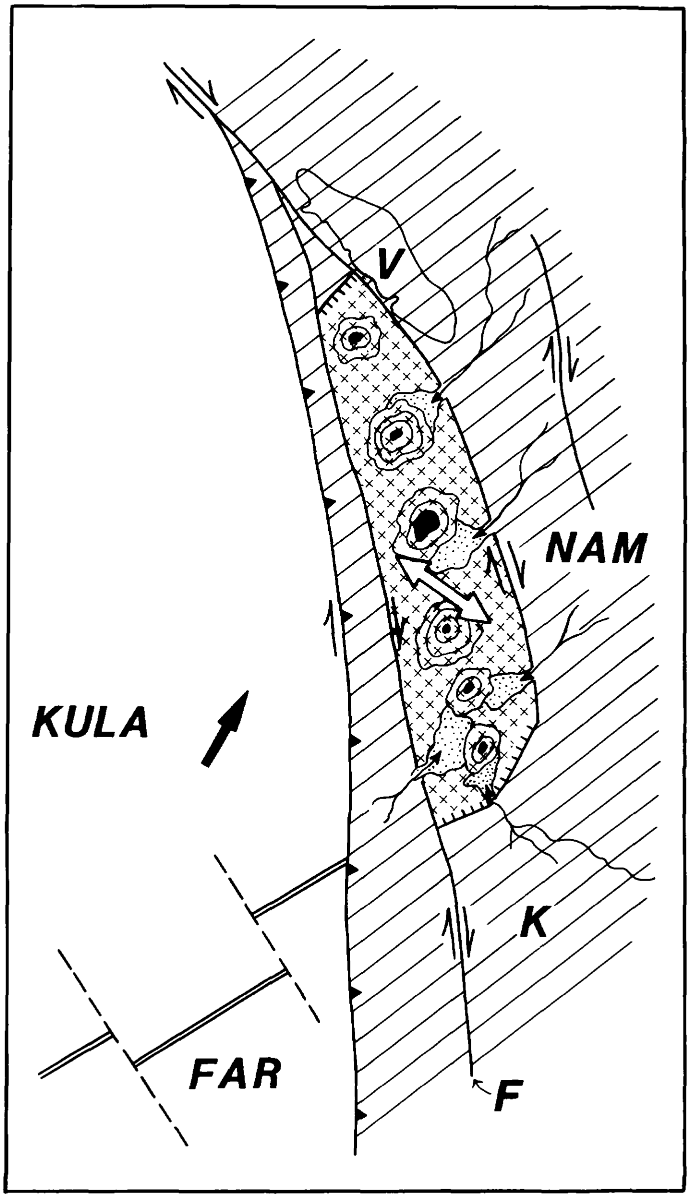

Figure 2. Diagram showing inferred continental-margin-rifting model for the origin of the Paleocene to lower middle Eocene oceanic basalt (x pattern) and oceanic islands (circular areas) in western Oregon and Washington. K, Klamath Mountains; V, Vancouver Island, B.C.; FAR, Farallon plate; KULA, Kula plate; NAM, North American plate; F, Fulmar fault. Arrow denotes direction of movement of the Kula plate relative to the North American plate (Engebretson and others, 1985).

configuration of the basins was likely inherited from the relief on the Siletz River and Crescent volcanic piles, because nearshore deposits as old as early Eocene unconformably onlap these volcanic highs (Bukry and Snavely, 1988; Snavely, 1991). Convergence between the Kula-Farallon and North American plates in late early Eocene time (~52 Ma) deformed the island chain and overlying marine sedimentary rocks against the North American buttress. In the southern part of the Oregon Coast Range, a set of southeast-dipping imbricate thrust sheets and fault-propagation folds deformed the Paleocene and lower Eocene oceanic basalts and overlying lower Eocene sedimentary rocks (Baldwin, 1974; Heller and Ryberg, 1983; Molenaar, 1985; Wells and Heller, 1988; Niem and Niem, 1990). In the central part of the Coast Range, the Siletz River Volcanics were faulted and folded prior to rapid downwarping and the deposition of the overlying mildly deformed Tyee Formation of early middle Eocene age (Snavely and others, 1976a; Bukry and Snavely, 1988).

This compressional event also deformed and uplifted continental terranes adjacent to the rift basin and accelerated erosion of pre-Tertiary rocks in the Klamath Mountains to the south and on Vancouver Island to the north. Debris flows and conglomerate derived from the Klamath Mountains occur along the southern margin of the Coast Range basin. In the southern Oregon part of the foreland basin, 2,000 m (6,560 ft) of arkosic, lithic, and feldspathic turbidite sandstone and siltstone of the lower middle Eocene Tyee Formation (Snavely and others, 1964; Lovell, 1969; Baldwin, 1974; Chan and Dott, 1983) were derived in part from an uplifted Klamath terrane and from the Idaho Batholith and adjacent terranes (Heller and others, 1985), buried pre-existing volcanic highs, and deformed lower Eocene sedimentary rocks. This sedimentary sequence laps across the tectonic boundary between the Klamath pre-Tertiary rocks and the Eocene oceanic basalts to the north and indicates that the Coast Range oceanic basement was accreted to the North American plate in early middle Eocene time (~50 Ma). Thick-bedded lithic quartzose sandstone and conglomerate of early middle(?) Eocene age in the Olympic core rocks (Tabor and Cady, 1978a; Snavely and others, 1986) represent material eroded from an uplifted pre-Tertiary terrane of Vancouver Island and the northern Cascade Range. In the Puget Sound area, streams transported large quantities of arkosic and lithic sand into the northern part of the basin across broad low-lying flood plains. The coal-bearing continental fluvial deposits, represented by the lower part of the Puget Group (Wolfe and others, 1961), the Chuckanut Formation (McLellan, 1927; Johnson, 1984), and the Swauk Formation (Russell, 1900; Tabor and others, 1984), formed in lowland areas. Part of this coarse clastic material may have been transported westward through submarine channels into the deeper parts of the basin to form turbidite fans. Some highly deformed lower and middle Eocene thick-bedded carbonaceous, lithic and arkosic sandstone units within the Olympic core rocks (Tabor and others, 1972; Tabor and Cady, 1978b) and in the Cape Flattery coastal area (Snavely and others, 1986) may be marine counterparts of these continental deposits.

LATE MIDDLE EOCENE TO LATE EOCENE

CONTINENTAL MARGIN MAGMATISM

Tholeiitic volcanism continued along the continental margin between 44 and 37 Ma, although the major volcanic centers became restricted to southwest Washington and the northern and central Oregon Coast Range (MacLeod and Snavely, 1973). The lavas were erupted from regional dike swarms that trended northeast before rotation. This orientation suggests a transtensional relationship to the right-lateral Fulmar fault (Wells and others, 1984). The basalts are chiefly subaerial; however, pillow lava and breccia in the lower part of these units intertongue laterally with deep-water siltstone of the upper middle Eocene Yamhill and the upper Eocene Nestucca Formations (Snavely and others, 1990a). These basalt flows and breccia include the Grays River volcanic rocks of southwest Washington (Livingston, 1966; Wells, 1981; Walsh and others, 1987), and the Tillamook Volcanics in northwest Oregon (Warren and others, 1945; Snavely and others, 1970; Magill and others, 1981; Wells and others, 1983; Niem and Niem, 1985). They were followed closely by the Yachats Basalt (Snavely and MacLeod, 1974), and the basalts of Cascade Head (Snavely and Vokes, 1949; Snavely and others, 1990b) in central coastal Oregon. The volcanic rocks are commonly porphyritic and have a wide range in composition, ranging from tholeiitic to alkalic basalt, basaltic andesite, and dacite. This compositional range suggests that the basaltic magma that produced these volcanic rocks was differentiated in high-level magma chambers before extrusion.

BASIN FORMATION AND SEDIMENTATION

Although differential uplift occurred in the areas of subaerial volcanism, such as the Heceta Head-Cape Perpetua area on the central Oregon coast (Snavely and MacLeod, 1974), regional downwarping occurred in most places in the forearc basin. Bathyal thin-bedded siltstone and sandstone were unconformably deposited on lower Eocene oceanic basalt and sedimentary rocks. The geometry of post-middle Eocene deposits was controlled in part by the distribution of thick upper Eocene volcanic sequences. For example, a west-trending ridge of Yachats Basalt separates the Coos Bay basin from the Newport embayment to the north. Other coastal basins appear to be fault controlled. The Tillamook embayment in northwest Oregon is bordered by a major northwest-trending en echelon fault zone that traverses the entire Coast Range (Wells and others, 1983).

In the northern part of the Olympic Peninsula, the middle and upper Eocene siltstones of the Aldwell Formation (Brown and others, 1960) overlapped older sedimentary rock to rest unconformably upon basalts of the lower Eocene Crescent Formation. The basal contact is marked in places by beds 10 to 30 m thick of cobble and boulder conglomerate derived from the underlying Crescent Formation. In the north-central part of the Oregon Coast Range, bathyal siltstone of the upper middle Eocene Yamhill Formation (Baldwin and others, 1955; Bukry and Snavely, 1988) unconformably overlaps folded strata of the Tyee Formation to rest upon basalt of the Siletz River Volcanics (Wells and others, 1983; Snavely, 1987). In the northern part of the Oregon Coast Range, the Yamhill Formation intertongues with pillow lavas and breccia of the middle Eocene Tillamook Volcanics (Wells and others, 1983; Snavely and others, 1990a).

A water-laid dacitic tuff bed up to 30 m thick occurs at or near the base of the Yamhill Formation in the central part of the Oregon Coast Range. This tuff unit is locally exposed from Florence northward to Dolph, a distance of more than 150 km. The source of ash that forms this tuff bed was most likely vents along an ancestral Cascade "arc." If this interpretation is correct, volcanism in the Oregon Cascades started about 44 Ma.

During the middle and late Eocene, streams transported large quantities of arkosic sand to a broad, low-lying coastal plain that bordered the eastern and southern parts of the forearc basin. Coal-bearing continental beds greater than 3,500 m (11,500 ft) thick are represented by the Puget Group (Wolfe and others, 1961) and the Cowlitz and Skookumchuck Formations (Snavely and others, 1958) in Washington, and the Coaledo Formation (Allen and Baldwin, 1944; Dott, 1966) in southwest Oregon. Some of this coarse clastic material undoubtedly was transported along channels into shelf basins and formed submarine fans and turbidite deposits. These continental beds interfinger with both Cascade-derived lavas and with coastal tholeiitic lavas, thus tying the middle Eocene tholeiites to the continental shelf.

FOREARC DEFORMATION

In the latest Eocene (~37 Ma), the forearc basin was deformed over a broad front. Regional uplift that accompanied this convergence segmented and shoaled the forearc region to produce a number of shelf basins that deepened westward. Erosion of uplifted middle and upper Eocene subaerial volcanic piles, such as the Tillamook Volcanics and the Yachats Basalt, produced thick deposits of fossiliferous basaltic sandstone and conglomerate that fringed the basalt highlands (Snavely and others, 1990a, 1990b; Bukry and Snavely, 1988). In the northernmost part of the forearc basin, two contrasting styles of deformation seem to support oblique subduction as the driving force. The first is north-south compression, as documented by major thrust faulting in the late middle Eocene along the Crescent and other major faults (fig. 3, MacLeod and others, 1977; Snavely and others,

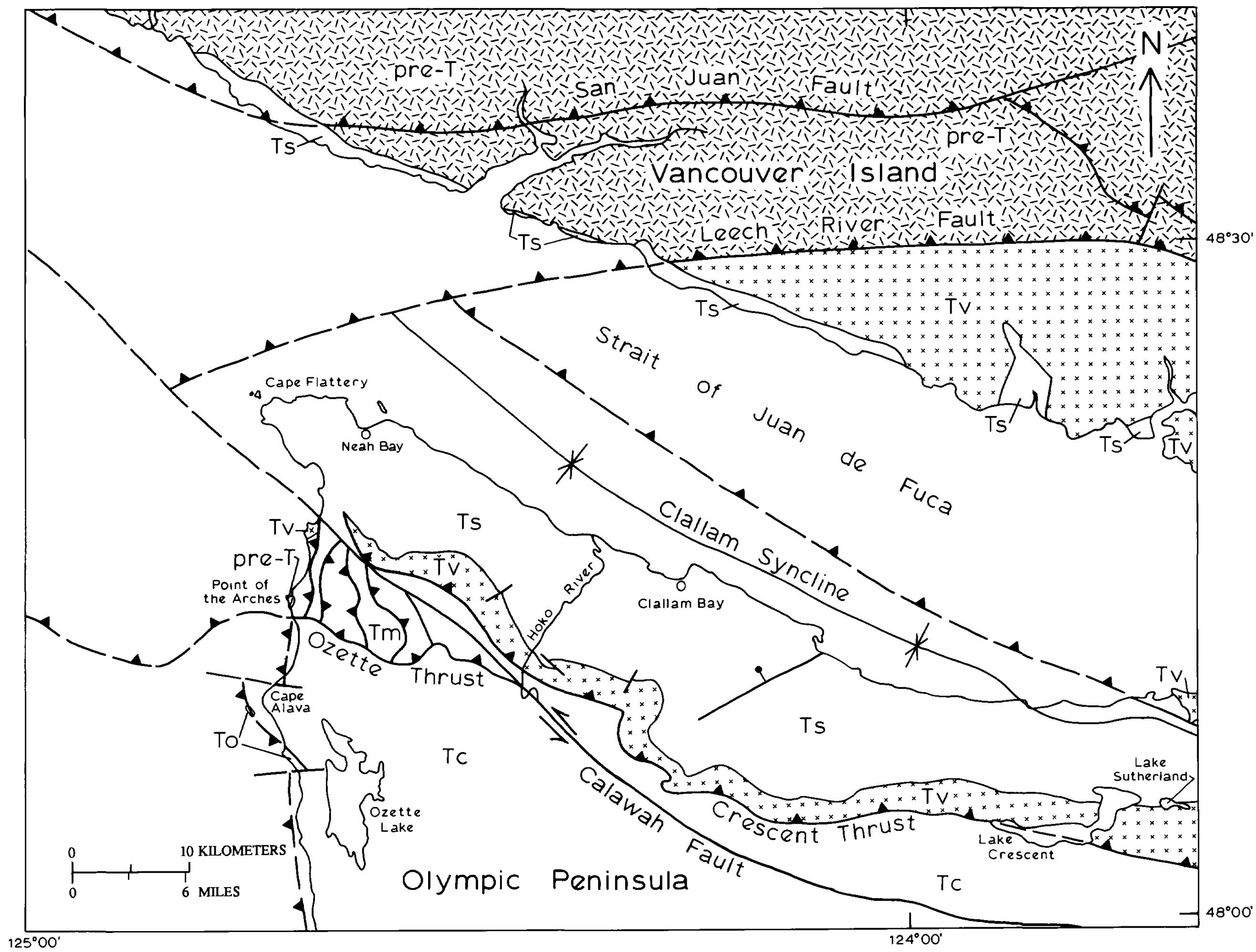

Figure 3. Generalized geologic map of the region adjacent to Cape Flattery, showing locations of major onshore faults and their offshore extensions (modified from MacLeod and others, 1977, and unpublished maps by Snavely). Ts, undivided Tertiary sedimentary rocks; To, upper Oligocene sandstone and conglomerate; Tm, overthrust pre-Tertiary to upper Eocene broken formation above Ozette thrust; Tc, highly deformed Eocene sandstone and siltstone and other rocks of the Olympic core; Tv, Eocene pillow basalt, breccia, associated dikes and sills of the Metchosin Volcanics (Clapp, 1917) on Vancouver Island and the Crescent Formation in Washington; pre-T, undivided pre-Tertiary igneous and metamorphic rocks on Vancouver Island and at the Point of the Arches.

1986). This resulted from northward movement of the Olympic-Coast Range Paleogene terrane against the buttress of pre-Tertiary rocks on Vancouver Island. Resulting erosion of uplifted pre-Tertiary terranes on southern Vancouver Island supplied coarse clastic debris to the northern part of the foreland basin to form the conglomerate-rich upper Eocene Lyre Formation (Brown and others, 1956; Snavely and others, 1986, 1989) along the northern Olympic Peninsula. The second deformation style, which occurred at about the same time, formed melange and broken formation of late Eocene age that were underthrust along the west side of the Olympic Peninsula (Snavely and Kvenvolden, 1989), implying continued subduction during north-south compression of the Coast Range.

Seismic-reflection profiles and subsurface data from deep test wells on the Oregon continental shelf (Snavely and others, 1980b, 1982) also show a regional unconformity at the base of upper Eocene siltstone (lower Refugian Stage). These strata unconformably overlie folded and faulted rocks as old as early Eocene and overlap the Fulmar fault (Snavely and others, 1980b; Snavely, 1984). Also, in several areas in the northwesternmost part of the Olympic Peninsula, strata of early Refugian age onlap melange and broken formation of middle and late Eocene age (Snavely and others, 1986).

OLIGOCENE TO MIDDLE MIOCENE

BASIN DEVELOPMENT

Rapid subsidence occurred in the forearc basin during Oligocene and early Miocene time, and more than 2,500 m (8,200 ft) of bathyal tuffaceous siltstone and arkosic sandstone were deposited in axial parts of the basin. On the Oregon continental margin, these strata are represented by tuffaceous siltstone of the Alsea Formation of Oligocene age (Snavely and others, 1975) and the Nye Mudstone of early Miocene (Saucesian Stage) age (Vokes and Snavely, 1948; Snavely and others, 1964). In the late Oligocene, high-energy deltaic deposits of pumiceous coarse-grained sandstone, such as the Yaquina Formation (Snavely and Wagner, 1963; Goodwin, 1973), were deposited in places along the eastern margin of the basin. In the deep marginal Tofino-Fuca basin along the north side of the Olympic Peninsula, more than 2,500 m (8,200 ft) of turbidite sandstone and siltstone of the Makah and Pysht Formations were deposited from the Oligocene to the early Miocene (Snavely and others, 1978, 1980a, 1986). The Makah Formation includes a major submarine landslide deposit (the Jansen Creek Member) that is composed of sediments derived from southern Vancouver Island (Niem and others, 1989). This basin shoaled in the early Miocene, and nearshore coal, sandstone, and conglomerate of the Clallam Formation were deposited (Gower, 1960; Addicott, 1976).

CONTINENTAL MARGIN MAGMATISM

Volcanic activity in the Cascade arc contributed large quantities of ash and pumiceous tuff-breccia to the forearc basin. Cascade-derived Oligocene mudflow conglomerate and thick (10 m) pumice beds occur as far west as the present coastline (Snavely and others, 1975). Near the late Eocene to middle Oligocene strandline, which lay near the present foothills of the Oregon Cascade Range, andesitic and dacitic tuff-breccia and volcaniclastic beds are complexly intercalated throughout much of the marine sequence.

In the central Oregon Coast Range, small volumes of highly evolved magmas were erupted and intruded into the marine strata. Camptonites, nepheline syenites, and ferrogabbros were emplaced between 34 and 30 Ma, roughly contemporaneous with the end of major late Eocene dextral slip faulting along the Fulmar fault and related faults to the east. This magmatism represents the final episode of rift-related magmatism in the Coast Range.

DEFORMATION

Onshore deformation during the Oligocene and early Miocene occurred throughout western Oregon and Washington, and was probably most intense in the Olympic Mountains. K/Ar dating of low-grade metamorphic rocks from the Olympic core rocks by Tabor (1972) suggests regional uplift at about 29 Ma. A mudflow unit of late Oligocene age that contains olistostromal blocks of basalt and graywacke derived from the Olympic core rocks provides evidence of this episode of uplift. The unit can be traced intermittently along the west side of the Olympic Peninsula from near Taholah northward to the Point of the Arches, a distance of more than 100 km (62 mi) (Snavely, unpublished mapping). However, in the Tofino basin along the north side of the peninsula, deposition appears to have been continuous during the late Oligocene and early Miocene with lenticular channel-fill deposits that contain conglomerate clasts derived from Vancouver Island (Snavely and others, 1980a).

Along the central Oregon coast, two tholeiitic basalt units are interbedded with middle Miocene sandstone and siltstone. The older—the Depoe Bay Basalt—is petrochemically identical to the Grande Ronde Basalt, and the younger Cape Foulweather Basalt is petrochemically identical to the Frenchman Springs Member of the Wanapum Basalt of the Columbia River Basalt Group (Snavely and others, 1973). The Depoe Bay Basalt extends more than 16 km seaward and was penetrated in several of the test wells at depths as much as 2.5 km (1.5 mi) (Snavely, 1984). The Cape Foulweather Basalt, however, is restricted to the inner shelf. Sills and flows of Depoe Bay Basalt are widespread in the northern Oregon Coast Range and on the continental shelf (Snavely and Wells, 1984; Snavely and McClellan, 1987; Niem and others, 1990). The stratigraphic and petrologic similarity between the coastal basalts and correlative units on the Columbia Plateau led some workers (Beeson and others, 1979) to suggest that the coastal basalts are invasive tongues of the Columbia River Basalt Group that erupted on the plateau. This may explain most of the coastal Miocene basalt outcrops, although it is hard to explain intrusions of Depoe Bay Basalt into volcanic rocks as old as early Eocene in the central coastal area of Oregon (Snavely and others, 1990a).

Regional uplift in the forearc basin in the early Miocene (about 20 Ma) restricted marine deposition to the west flank of the Oregon Coast Range and the adjacent continental shelf, and to the Coos Bay, Newport, Astoria, Grays Harbor, and Tofino-Fuca structural embayments (fig. 1). Nearshore deltaic and strandline sandstone and siltstone deposits of the lower and middle Miocene Astoria Formation (Cooper, 1981) grade westward into predominantly bathyal siltstone in the deep marginal basin off Oregon (Snavely and others, 1982). Along the central and northern Oregon coast, the Astoria Formation rests on strata ranging in age from late Eocene to early Miocene. In the deep marginal basin on the Oregon continental shelf, seismic-reflection profiles and drill-hole data indicate that sedimentation was virtually continuous, and siltstone strata correlative with the Nye Mudstone and Astoria Formation form a single rock-stratigraphic unit (Snavely and others, 1980b).

On the Olympic coast, lower and middle Miocene thick-bedded sandstone and thin-bedded siltstone and conglomerate of both shelf and bathyal depositional environments lap onto Eocene melange and broken formation (Rau, 1975, 1979; Snavely and Kvenvolden, 1989). These deposits were intensely folded and faulted during plate convergence in the late middle Miocene.

LATE MIDDLE MIOCENE TO PLIOCENE

Regional deformation occurred in western Oregon and Washington and on the adjacent continental shelf in the late middle Miocene, between 15 and 10 Ma. Uplift of the Coast Range-Olympic Mountains formed highland areas that were rapidly eroded and supplied large amounts of clastic debris to elongate basins on the continental shelf. On the Oregon inner shelf, strata as young as middle Miocene were folded and uplifted, truncated by erosion, and subsequently downwarped and overlapped unconformably by upper Miocene strata (Snavely and others, 1980b). Uplift was greatest on the Olympic Peninsula, perhaps partly owing to isostatic uplift of the thick prism of melange and broken formation that was subducted during late middle Miocene and partly owing to northward motion of the Coast Range. Alternatively, Brandon and Calderwood (1990) suggest that uplift of the core rocks may be a response to development of a flexure in the subducting slab beneath the Olympic Mountains.

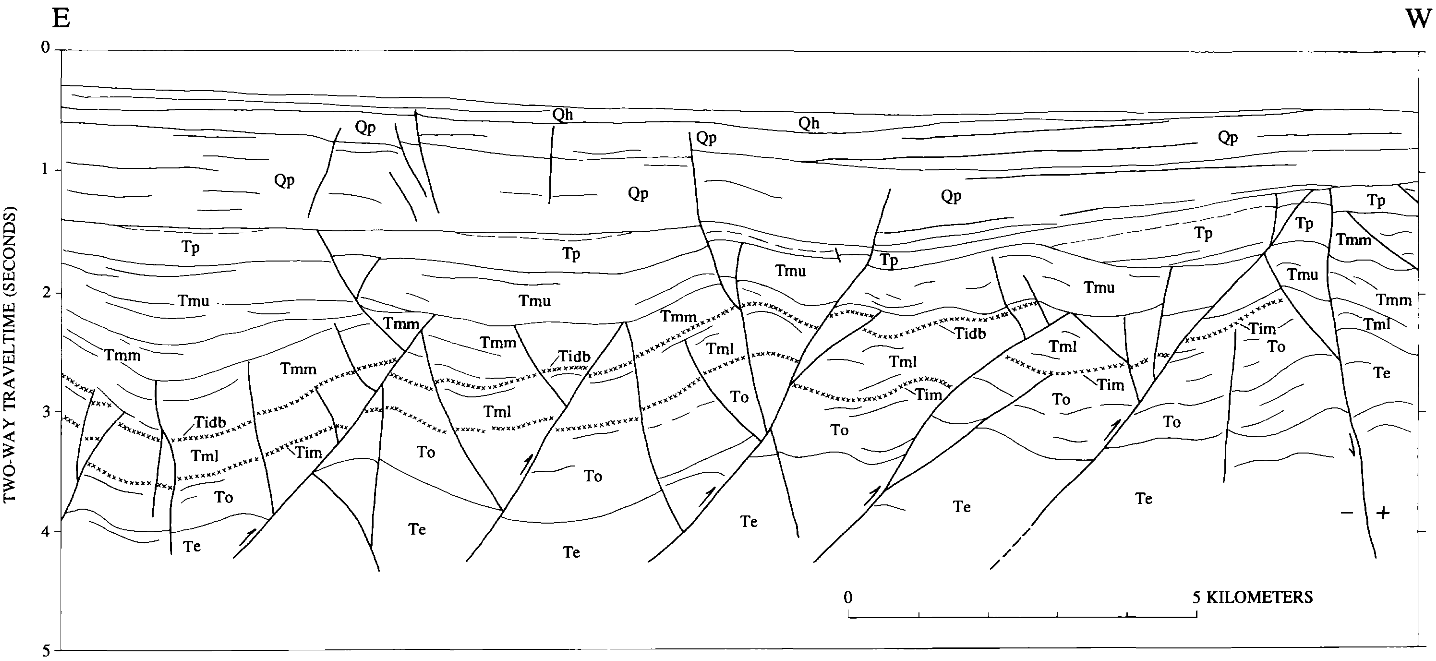

Figure 4. Geologic interpretation of 24-channel seismic-reflection profile, (USGS line WO77-11), collected off the central Oregon coast near latitude 45 degrees. The family of east-dipping thrust faults that form the fault propagation folds are considered to be normal faults that were reactivated during late middle Miocene transpression. Symbols: Qh, Holocene; Qp, Pleistocene; Tp, Pliocene; Tmu, upper Miocene; Tmm, middle Miocene; Tml, lower Miocene; To, Oligocene; Te, late Eocene; small x's with symbol Tidb, basalt flow, with symbol Tim, basalt sill; faults, half arrows indicate direction of movement on thrust faults, vertical strike-slip faults, +, towards; -, away from reader. Vertical exaggeration approximately 2:2.

Normal faults on the Oregon shelf were reactivated as thrusts during late middle Miocene transpression and formed a family of landward-dipping fault-propagation folds (fig. 4). Although most folds were truncated by the late Miocene unconformity, movement on some faults gently folded strata as young as Pleistocene.

BASIN DEVELOPMENT

In the late Miocene and Pliocene, episodic downwarping of a deep marginal basin off Oregon was virtually continuous, and more than 2,000 m (6,560 ft) of sand and silt were deposited. Upper Miocene and Pliocene deposits thinned against the eastern border of the marginal basin and against older mid-shelf structural highs (Snavely and others, 1980b; Clarke and others, 1981). Shelf basins formed landward of folded and thrust-faulted upper Oligocene to upper middle Miocene melange welts. On the central and southern Washington shelf, as much as 2,000 m (6,560 ft) of upper Miocene and Pliocene sediment accumulated on a thick accretionary wedge of melange and broken formation of late Oligocene(?) to late middle Miocene age (Rau, 1975, 1979; Snavely and Wagner, 1982). The Miocene and Pliocene strata thin against growing anticlines or diapirs, the cores of which consist of upper Oligocene to middle Miocene melange and broken formation. Adjacent to these diapiric structures numerous unconformities, growth faults, and gravity slides occur within younger strata, all of which likely reflect episodic uplift (fig. 5; also see Snavely and Wagner, 1982).

Off northwest Washington and southern Vancouver Island, upper Miocene strata rest unconformably on older Tertiary rocks (Shouldice, 1971; Snavely and Wagner, 1980).

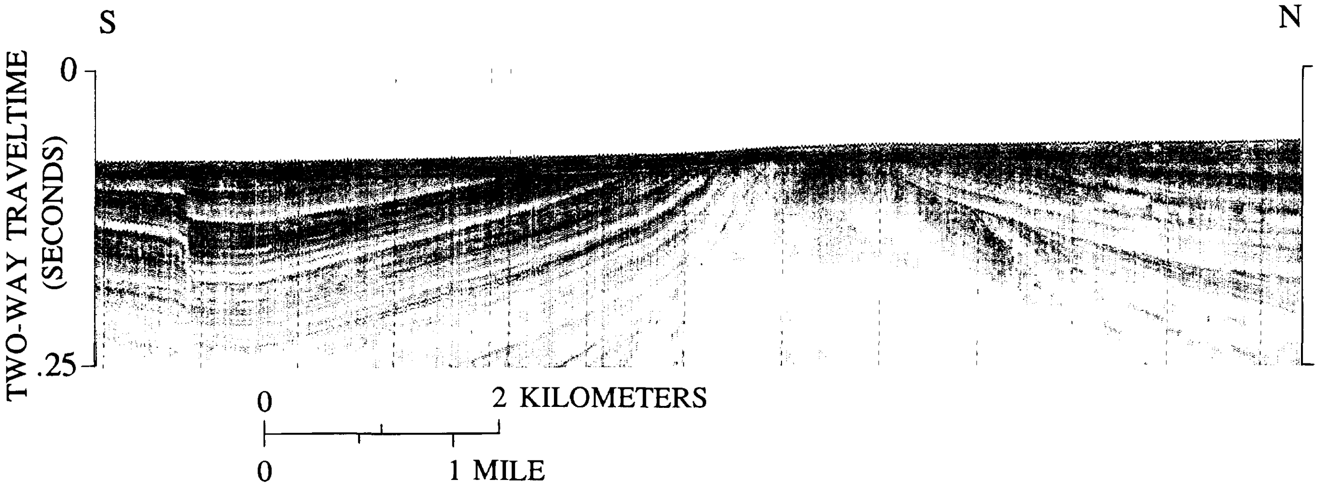

Figure 5. High-resolution (Uniboom) single-channel seismic-reflection profile (USGS line WO80-18) across an asymmetric diapiric structure off the mouth of the Columbia River. Strata of Pleistocene age onlap and thin against this growing structure. Marked unconformity on north side of diapiric structure reflects episodic uplift of the core, which appears to be bounded by a growth fault on its south side. Note fault near south side of profile that offsets uppermost Pleistocene strata but not sea floor sediments. Vertical exaggeration approximately 12:1.

Although most strata of this age are restricted to the shelf, upper Miocene shallow-water sandstone and siltstone occur in a small isolated basin along the west side of the Olympic Peninsula in the lower Bogachiel River Valley (Rau, 1979), and in fault-bounded blocks along the coast north of Taholah (Rau, 1970; 1975). Upper Miocene strata also crop out on the southern Oregon coast near Coos Bay (Addicott, 1976; Armentrout, 1980).

In a filled trench along the base of the slope (fig. 6), about 3.5 km (11,500 ft) of strata occur above an upper Miocene oceanic crust (Kulm and Fowler, 1974; Snavely and others, 1980b; Carlson and Nelson, 1987; Snavely, 1987). From velocity analysis, it is estimated that as much as half of this fill is of late Miocene and Pliocene age.

PLEISTOCENE TO HOLOCENE

Pleistocene and Holocene sediments extend across most of the continental shelf of Oregon and Washington, and Neogene strata are exposed on the sea floor only on large banks such as Stonewall, Heceta, and Nehalem (fig. 1; Kulm and Fowler, 1974; Snavely and Wagner, 1980; Snavely and others, 1980b; Clarke and others, 1981; Carlson and Nelson, 1987; Snavely and McClellan, 1987). These Quaternary deposits of fine sand and silt are thickest (500 m; 1,640 ft) on the inner shelf and in basins between compressional folds on the outer shelf and lower slope. Several unconformities occur within this sequence, indicating episodic downwarping of the basins as well as uplift of diapiric structures during deposition (fig. 5). On the abyssal plain, more than 1,800 m (5,900 ft) of strata are most likely of Pleistocene and Holocene age (Kulm and Fowler, 1974; Snavely and others, 1980b; Carlson and Nelson, 1987).

Pleistocene uplift of the Olympic Mountains and the Oregon and Washington Coast Ranges shed coarse clastic debris that overwhelmed hemipelagic sediments along the eastern flanks of the marginal shelf basin. Uplifted Pleistocene channel-fill deposits along the coast are as much as 60 m (197 ft) thick and contain beds of peat (Snavely, 1948). Glacio-fluvial sand and gravel from alpine glaciers in the Olympic Mountains and from the

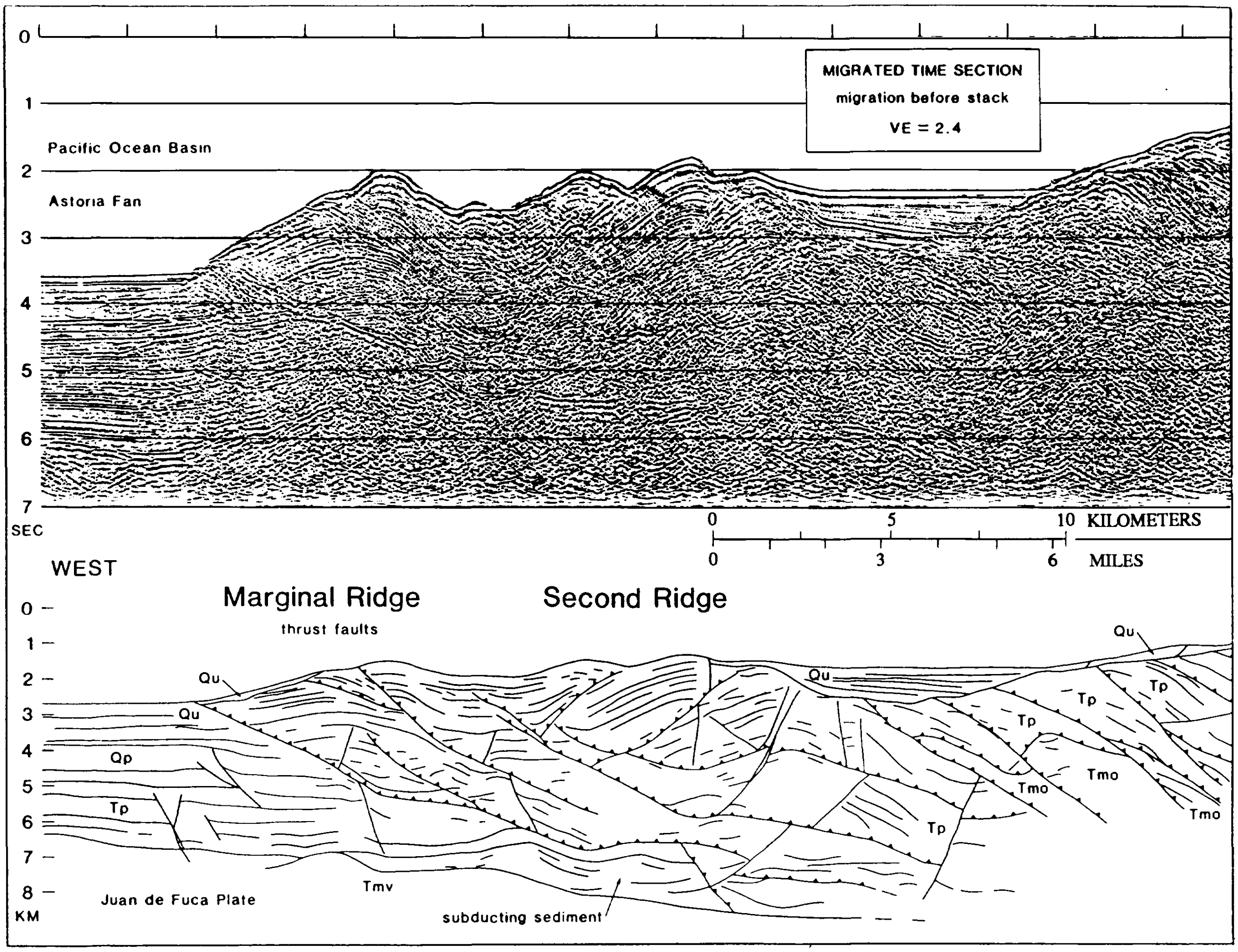

Figure 6. Geologic interpretation of a migrated 24-channel seismic-reflection profile (USGS line WO76-5) across the lower continental slope of central coastal Oregon showing filled trench deposits and a deformation front consisting of a family of fault propagation folds. Symbols on depth sections are: Qu, Holocene; Qp, Pleistocene; Tp, Pliocene; Tmv, upper Miocene oceanic crust; Tmo, Oligocene to middle Miocene melange and broken formation. Depth section in lower panel, after Snavely and others (1987).

Fraser lobe (Easterbrook, 1969) of the continental ice sheet were deposited along the seaward margin of the Olympic Peninsula and extend onto the inner shelf.

REGIONAL STRUCTURE

The convergent margin of Oregon and Washington consists of three major tectonic elements (fig. 1): 1) the Coast Range terrane, an oceanic basalt-floored terrane which comprises most of the onshore region between Vancouver Island and the Klamath Mountains and extends westward beneath the inner continental shelf; 2) the Fulmar terrane, a fault sliver on the outer continental shelf, possibly of continental derivation, which is emplaced outboard of the oceanic terrane; and 3) the accretionary assemblage, an imbricate structural complex of offscraped and underplated sedimentary packages that makes up the continental slope and outer shelf. The structure and arrangement of these terranes reflect a long history of oblique convergence during which margin-parallel strike slip, oblique extension, and continental margin compression have all played a part. The importance of dextral slip faulting along the Pacific Northwest convergent margin has only recently been realized, with the discovery of offshore faults like the Fulmar fault (Snavely and others, 1980b; Snavely, 1987) and abundant paleomagnetic evidence for clockwise rotation of coastal regions (see Wells and Heller, 1988 and Wells, 1989 for summary).

COAST RANGE TERRANE

The structure of the Coast Range terrane is largely the result of the Paleocene to early Eocene oblique rifting of the margin (fig. 2) which produced the oceanic basalt basement of the terrane, and the subsequent Eocene compressional event which folded the basalts against the continental margin. On the continental shelf, the tectonic boundary between the tholeiitic basalt Coast Range basement and the pre-Tertiary continental rocks is exposed near Roseburg in the southern Oregon Coast Range and at the southern tip of Vancouver Island (fig. 1). At Roseburg, the Paleocene pillow basalts and overlying lower Eocene turbidites are folded and thrust southeastward beneath pre-Tertiary accreted terranes marginal to the Klamath Mountains (Baldwin 1974; Heller and Ryberg, 1983; Niem and Niem, 1990). The northeast-trending folds and faults are unconformably onlapped by gently dipping middle Eocene turbidites of the Tyee Formation, thus limiting the time of compression to about 50 Ma. On Vancouver Island, lower Eocene tholeiitic basalts of the Metchosin Formation are thrust to the northeast beneath the Leech River Schist along the Leech River Fault (Clowes and others, 1987). The schist has a late middle Eocene K/Ar cooling age of about 42 Ma, which has been interpreted as the time of accretion of the oceanic terrane to the continent (Fairchild and Cowan, 1982). This age is much younger than that inferred from stratigraphic relationships in the southern Oregon Coast Range and Klamath Mountains and implies a complex tectonic history for the Oregon-Washington continental margin.

The western boundary of the oceanic basement is the Fulmar fault on the outer continental shelf of Oregon. It is presumed to extend at least 200 km (125 mi) north-south on the basis of a linear aeromagnetic gradient (Bond and Zeitz, 1987) that Snavely and others (1980b) interpreted to be the western edge of Coast Range basaltic basement. Seismic-reflection profiles and offshore deep test wells (Snavely and others, 1982) confirm that a steep fault separates lower Eocene oceanic basalt on the east from lower Eocene quartzose lithic sandstone of continental source on the west. The Fulmar fault is interpreted to be a major Eocene right-lateral strike-slip fault which formed the western margin of an oblique pull-apart basin in which the Coast Range basalts were erupted (Snavely, 1987; Wells and others, 1984). To the south, the fault intersects the coast south of Coos Bay just north of Five Mile Point and is inferred southward into northern California either along the Coquille River fault (Snavely, 1987) or on the continental shelf (Clarke, in press). Interpretation of multichannel seismic-reflection profiles indicates that the fault extends along the mid-shelf northward to about latitude 45° where displacement may have been transferred inboard to a comparable fault bounding the eastern margin of the Coast Range basement. However, the eastern boundary of the Coast Range basement is covered by younger volcanic rocks of the Cascade arc.

DEFORMATION OF THE COAST RANGE-OLYMPIC TERRANE

Folds and faults that formed during accretion of the Coast Range basement to the continent have systematic trends which have partly controlled the structural grain of later deformation. Fold axes in uplifts of pillow basalt basement generally trend northeast in Oregon and northwest in Washington, apparently reflecting subsequent greater clockwise tectonic rotation of Oregon (70 degrees) when compared to Washington (~30 degrees) (see Wells, 1989 for a summary). Some of these transverse folds and related thrust faults have been active into the late Cenozoic and possibly are boundaries for tectonically rotated blocks (Wells and Coe, 1985). In southwest Washington, northwest-trending folds and thrust faults extend eastward into the western Cascade Range where they deform rocks as young as Miocene (Snavely and others, 1958; Walsh and others, 1987). In Oregon, northeast-trending folds and boundary faults largely became inactive after Eocene time and have been overprinted by Neogene north to northwest-trending faults and folds (Wells and others, 1983; Niem and Niem, 1985; Snavely and others, 1990a). The northwest-trending folds are compatible with moderate shortening of the forearc during oblique convergence of the Farallon plate.

Late Cenozoic north-south compression of the Coast Range-Olympic terrane is suggested by widely spaced, east-west reverse faults and related folds in rocks as young as Quaternary. These structures include (among others), the Clallam syncline and parallel tight asymmetric folds along the north flank of the Olympic Mountains (Brown, Gower, and Snavely, 1960; Gower, 1960), the Doty-Grays River-Columbia River fault zone in southwest Washington (Pease and Hoover, 1957; Snavely and others, 1958; McKee and Wolfe, 1968; Wells, 1981) and the Cape Falcon fault zone in northwest Oregon (Niem and Niem, 1985) that deforms middle Miocene flows of the Columbia River Basalt Group.

A coastal system of northwest-trending dextral faults and local conjugate northeast-trending sinistral faults is consistent with north-south compression of the Oregon-Washington Coast Range terrane (Wells and Coe, 1985; Niem and Niem, 1985; Wells and others, 1983, Snavely and others, 1976a, b, c). However, the smooth increase in clockwise rotation toward the coast (Wells, 1989) also suggests that the coastal region is under dextral shear, probably as a result of long term oblique subduction along the plate boundary. Block rotation is probably accommodated by the abundant west-northwest- and northwest-trending sinistral faults mapped along the coast (eg. Wells and Coe, 1985; Snavely and others, 1990a, b). These faults cut the youngest units (Pomona Member of the Columbia River Basalt Group at 12 Ma) and commonly exhibit well developed subhorizontal slickensides. Regionally significant dextral faults extend inboard into the Yakima foldbelt just east of the Cascade arc (Toland and Reidel, 1989). Fault displacements are difficult to determine, but the increase in tectonic rotation of the Columbia River Basalt Group toward the plate boundary (fig. 7) suggests that cumulative, post-15-Ma dextral slip may exceed 100 km (62 mi) between the coast and the unrotated Columbia Plateau 300 km (185 mi) to the east (England and Wells, in press). Apparently, much of the late Cenozoic margin parallel component of oblique subduction is being converted to strike-slip deformation and northward transport of the continental margin.

Definitive evidence for north-south transpression during the Quaternary is documented in road cut exposures along U.S. Highway 101 on the east side of Morse Creek, 6 km (3.8 mi) east of Port Angeles. Here siltstone beds of the Oligocene Twin River Formation are thrust northward over early(?) Pleistocene alpine drift (Brown and others, 1960). This poorly bedded unit, which is overturned and dips about 40 degrees to the south, in turn, is unconformably overlain by north-dipping (30-50 degrees) moderately well-bedded sand, gravel, and till with scattered clasts of Oligocene siltstone eroded off the fault scarp. Broadly channelized flat-lying deposits of Fraser outwash gravels unconformably overlie the northward-dipping outwash and till unit. In the Strait of Juan de Fuca, Wagner and Tomson (1987) used seismic-reflection data to map numerous west-trending folds and faults that involve sediments as young as Holocene. These structures reflect deformation of a northward moving coastal block against the pre-Tertiary Vancouver Island buttress (Snavely, 1987).

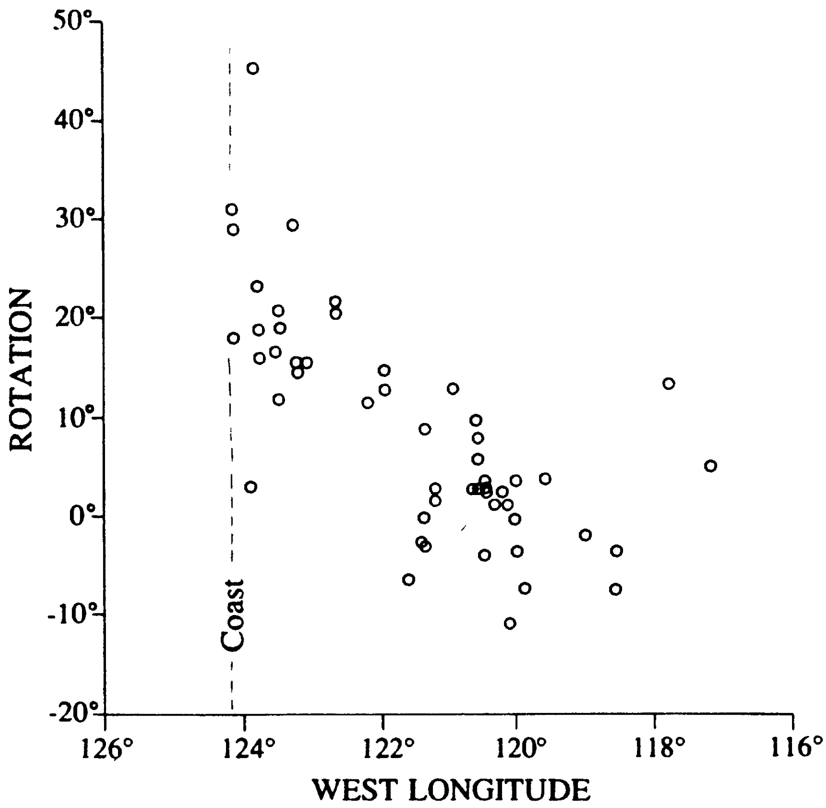

Figure 7. Clockwise paleomagnetic rotations of Miocene Columbia River Group in Oregon and Washington plotted on an east-west profile. Rotations increase westward from the Columbia Plateau toward the plate boundary, implying a driving force acting along the plate boundary (after England and Wells, in press).

The late Cenozoic north-south compression is compatible with compression axes determined from present day crustal earthquakes and well bore breakouts in the Pacific Northwest (Ludwin and others, in press; Zoback and Zoback, 1989; Werner and others, in press) and suggests growing influence of the Pacific plate during late Cenozoic deformation of western Oregon and Washington (Spence, 1989).

FULMAR TERRANE

The composition and extent of the Fulmar terrane can only be inferred from the seismic, aeromagnetic, and deep well data. It is thought to be a continental fragment that has been displaced northward outboard of the Coast Range oceanic basement. It may represent a piece of southern Oregon or northern California emplaced during regional dextral slip faulting along the continental margin. The Fulmar fault conforms to a regional pattern of latest Cretaceous to Eocene right-lateral faulting throughout the Pacific Northwest (Davis and others, 1978; Ewing, 1980; Tabor and others, 1984) and northern California (Blake and Jayko, 1986). Displacement on the Fulmar fault may be at least 200 km (125 mi) based on the northward extent of the outboard Fulmar terrane; however, geochemical similarities between Coast Range basalts and time-equivalent lower Eocene tholeiites from the allochthonous Yakutat block in the Gulf of Alaska (Davis and Plafker, 1986) suggest that larger displacements may be possible. Movement along this fault is contemporaneous with the formation of the Kula Plate and its rapid northward motion with respect to North America (Engebretson and others, 1985). The late Eocene end of motion on the Fulmar fault may correlate with the demise of the Kula plate at about 43 Ma, or it may record the northward migration of the Kula-Farallon-North America triple junction along the continental margin. More head-on convergence of the Farallon plate may have ended large-scale transcurrent motions and caused thrusting of the marginal basin floor and its sedimentary cover beneath the continental margin. The younger apparent ages for accretion of the oceanic basement in southern Vancouver Island may reflect progressive accretion of the marginal basin to the continent in the wake of the northward moving triple junction.

ACCRETIONARY WEDGE TERRANE

An imbricate stack of thrust-bounded packages of highly deformed Cenozoic sedimentary rocks forms the outermost tectonic belt of the Oregon-Washington convergent margin (see fig. 6 for example). The majority of this assemblage is offshore and its structure is inferred from seismic-reflection profiles and a few deep test wells. However, in the Olympic Mountains, the accretionary assemblage comes onshore where it can be studied with traditional field techniques (see for example, Stewart, 1974; Tabor and Cady, 1978a; Tabor, 1975; Rau, 1975, 1979; Snavely and others, 1986; Snavely and Kvenvolden, 1989).

The subduction complex of the Olympic Mountains forms the core of a broad anticlinal uplift in which imbricate packages of Eocene to Miocene turbidite rocks are thrust beneath Crescent Formation basalts of the Coast Range oceanic basement (fig. 1). The boundary between the oceanic basement and the accretionary wedge is a major thrust fault which juxtaposes middle(?) Eocene melange and broken formation of the Needles-Gray Wolf assemblage to the west against coherent strata of the peripheral rocks to the east (Tabor and Cady, 1978a; Snavely and others, 1986; Brandon and others, 1988). Reflection and refraction profiles interpreted from the Canadian Lithoprobe program indicate that these Eocene strata underplate the lower Eocene Metchosin Formation and pre-Tertiary rocks on southern Vancouver Island (Clowes and others, 1987). The thrust bounded sedimentary assemblages are younger to the southwest, with the upper Oligocene-lower Miocene rock assemblage exposed along the coast (Rau, 1975; 1979; Snavely and Kvenvolden, 1989). In the northwest Olympic Mountains, two coherent terranes have been thrust beneath the Crescent Formation basalts in the late middle Eocene—the Ozette terrane and the pre-Tertiary Point of the Arches terrane (Snavely and others, 1986).

TECTONIC UNDERPLATING

Geologic mapping in accretionary assemblages of the western Olympic Mountains (Snavely and others, 1986, 1989; Snavely and Kvenvolden, 1989) and interpretation of seismic profiles on the Vancouver Island margin (Clowes and others, 1987; Davis and Hyndman, 1989; Snavely and Wagner, 1981), on the Washington shelf (Snavely and Wagner, 1982), and on the Oregon continental slope (Snavely and others, 1985, 1987) indicate that strata ranging in age from middle Eocene to Pliocene have underplated older rocks along the convergent margin.

Reconnaissance geologic mapping along the west side of the Olympic Peninsula and interpretation of seismic profiles and subsurface data in Pan Am well P-0141 on the shelf led Snavely and Kvenvolden (1989) to speculate that the middle to upper Eocene Calawah melange and broken formation underplates the lower and middle Miocene Hoh melange along the coast. Farther south on the mid shelf off Grays Harbor, the upper Oligocene and middle Miocene Hoh melange is interpreted from seismic-reflection profiles to underplate upper(?) Miocene and younger strata along a master shear zone or decollement as shown in figure 8. On the inner shelf, however, the upper Oligocene and middle Miocene melange appears to underplate middle Eocene basalt(?) and middle and upper Eocene(?) strata as shown on the eastern part of the profile. Diapiric structures, which originate from overpressured melange developed below this megashear intrude the overlying upper(?)

Miocene and Pliocene strata (fig. 8). A land-sea geologic cross section just south of Grays Harbor (Snavely and Wagner, 1982) also shows that the upper Oligocene and middle Miocene melange underplates older rocks near the coastline and may extend eastward beneath Grays Harbor basin.

FAULT PROPAGATION FOLDS AND BLIND THRUSTS

Northeastward oblique subduction of the Juan de Fuca plate has shortened the post-upper Miocene(?) strata of the accretionary wedge to produce a group of fault propagation folds. These fault-bounded folds are well imaged on seismic profiles across the deformation front along the continental slope of Oregon and Washington. In Oregon, the vergence of these thrusts is eastward, whereas along the Washington slope the vergence is westward (Snavely, 1987). The change in the direction of vergence occurs just south of the Columbia River.

A west-trending multichannel seismic-reflection profile across the deformation front at the base of the slope off the mouth of the Columbia River (fig. 9) was generously made available to Snavely by Exxon Company, U.S.A. for inclusion in this report. This profile clearly images a group of fault propagation folds on the continental slope in strata of Pliocene and early (?)Pleistocene age. This fold-thrust belt is interpreted to be underplated by an eastward thickening melange wedge of late Oligocene to late Miocene age. The decollement between the Pliocene and Pleistocene sequence and the melange is sharply defined and truncates folds and faults in the upper plate. Most likely truncation of upper plate structures was by processes of subduction erosion as defined by Scholl and others (1980). The melange wedge overlies the gently dipping (~3 degrees) subducting Juan de Fuca plate that can be traced from the base of the slope eastward for about 55 km (35 mi). The thrust faults on the lower slope dip eastward, whereas the youngest thrust at the base of the slope at the west end of the profile dips westward. Snavely (1987) speculated that the change in direction of vergence of thrust faults along the continental slope of Oregon and Washington may have been controlled by the slope of the backstop against which the melange wedge accreted. A steep backstop is inferred to result in seaward vergence, whereas a gently dipping backstop resulted in landward vergence. On figure 9, the steep backstop formed by the strike-slip(?) fault near the eastern end of the profile produced thrusts with seaward vergence, whereas the gentle dipping backstop along the base of the slope produced the landward vergence of the westernmost thrust.

Fault propagation folds also occur inboard of the accretionary wedge on the Oregon continental shelf where numerous blind-thrusts offset rocks as young as middle Miocene (fig. 4). These blind thrusts die out in fault propagation folds, some of which gently warp strata as young as Pleistocene. One such fold in the deep marginal basin off central Oregon was the exploration target for the Standard-Union, Nautilus P-0130 well (Table 1), drilled in 1964 (Snavely and others, 1980b; Snavely, 1987).

Critical to the timing of formation of the blind thrusts and other structures on the continental shelf are widespread subaerial basalt flows of middle Miocene age (~16 Ma) assigned to the Depoe Bay Basalt (Snavely and others, 1973). These rapidly erupted flows can be traced westward from the coast over a wide area of the Oregon continental shelf (Snavely and Wells, 1984) and probably flowed onto the shelf from coastal vents during a global eustatic low stand (between cycles 2.3 and 2.4 of supercycle TB2 of Haq and others, 1987). Therefore, using the Depoe Bay Basalt flows as a time horizon, an episode of major transpressional tectonics that occurred on the Oregon continental margin can be documented in post-middle Miocene time and prior to the regional unconformity at the base of upper Miocene strata (about 10.5 m.y.). In addition, middle Miocene basalt sills and dikes are common both onshore and offshore (Niem and others, 1990).

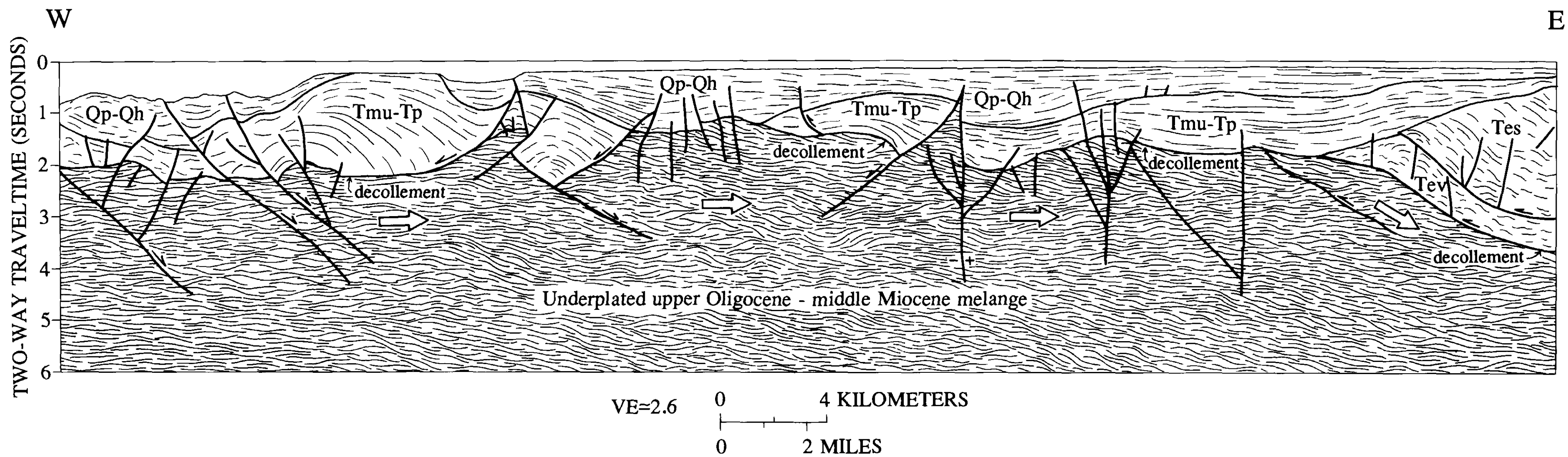

Figure 8. Interpreted time-section of migrated multichannel seismic-reflection profile on the continental shelf off Grays Harbor, Washington. The upper Oligocene and middle Miocene Hoh melange is inferred to underplate broadly folded strata of late Miocene and Pliocene age. Near the eastern edge of the profile, the Hoh melange appears to underplate middle(?) Eocene basalt and upper Eocene(?) strata. Symbols: Qp-Qh, undivided Pleistocene and Holocene sediments; Tmu-Tp, undivided upper Miocene and Pliocene strata; Tes, upper Eocene strata; Tev, middle Eocene basalt. Open arrows show direction of tectonic underplating.

Several seismic profiles that cross the upper continental slope also indicate that the shelf margin has collapsed along west-dipping listric faults (fig. 8). Narrow extensional half-graben basins bounded by these faults have been progressively infilled with upper Miocene(?) and Pliocene(?) sediments (Snavely and McClellan, 1987). Unconformities between these sequences most likely reflect episodes of downslope movement along basin-bounding listric faults owing to sediment loading.

NEOTECTONICS

The intense deformation recognized in Cenozoic strata of the Oregon-Washington convergent margin clearly records a prolonged history of episodic tectonism along the active plate boundary. The numerous unconformities on growing structures, the record of giant modern and ancient submarine slides such as the Jansen Creek Member of the Oligocene Makah Formation (Snavely and others, 1980a; Niem and others, 1989), and abundant debris flows in basin filling sequences all infer a past history of seismic events. There is ample evidence that this episodic deformation continues in the Quaternary.

OFFSHORE STRUCTURES

Seismic-reflection profiles across the deformational front along the continental slope of Oregon and Washington show that episodic underthrusting of the Juan de Fuca plate beneath the North American plate has produced a series of north- to north-northwest-trending, elongate, en enchelon anticlinal ridges bounded by thrust faults (Silver, 1972; Carson, 1977; Snavely and others, 1980b; Snavely, 1987). These ridges have bathymetric expression and uplift Pleistocene abyssal sediments as much as 1,100 m (3,600 ft) (Byrne and others, 1966; Carson and others, 1974; Kulm and Fowler, 1974; Snavely and others, 1980b; Snavely and Wagner, 1981; fig. 6, this report).

The profile off central Oregon (fig. 6) indicates that two lower slope basins formed landward of anticlinal folds in Pleistocene strata. The larger basin, which is near the base of the upper slope, contains as much as 800 m (2,625 ft) of Quaternary sediments and an unconformity within these basin deposits, thus indicating two distinct periods of uplift of the fault propagation fold that bounds the basin on the west. Along the axis of the deep marginal shelf basin off central Oregon, numerous unconformities occur in the Neogene sequence. Of particular interest is the fact that the sea floor itself is also downwarped along the axis of the basin. A family of north-trending faults along the east margin of the basin offsets the sea floor and coastal terrace deposits. We speculate that transpression across the basin episodically was relieved along this set of faults to produce the stacked unconformities along the axial part of the basin (fig.10).

Other recent deformation on the Oregon shelf suggests a complex relationship between normal faulting and growth of diapirs. A high-resolution line (fig. 11) on the inner shelf off northwest Oregon shows a broad 2-km (1.2 mi) -wide uplift of Pliocene(?) strata capped by a group of pinnacle-like features that rise 5-15 m (16-50 ft) above the sea floor. Observations during a submersible dive by L.D. Kulm, Oregon State University (written commun., 1988) , indicate that the walls of these features are nearly vertical and rock fall debris is not present on the intervening flat floors. Also, there apparently is little evidence of erosion that could have carved this topography, and the surface of some blocks have vertical striations (slickensides?). A multichannel profile across this pinnacle-crested fold indicates that this feature is a faulted diapiric structure bounded on the east by a normal (growth) fault. Our interpretation is that the crest of this diapir has been subjected to extension over the 2 km (1.2 mi) fold, resulting in the development of horst and graben structures along the crest of the fold. The lack of significant erosion on the walls of these

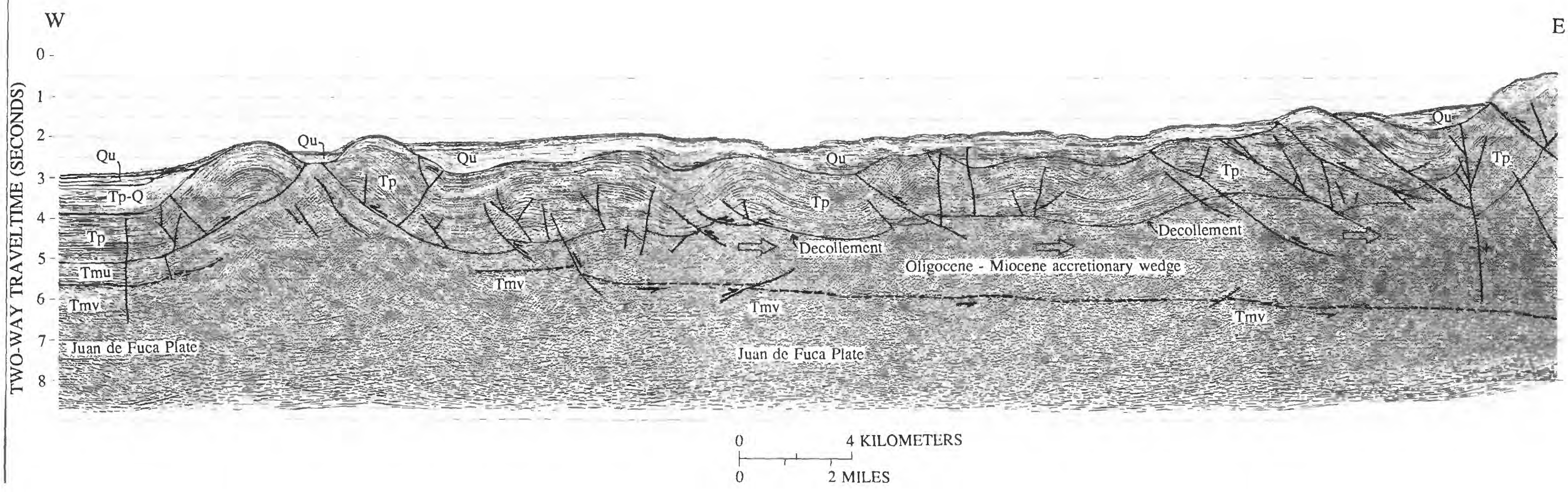

Figure 9. Migrated multichannel seismic-reflection (profile provided by Exxon Co. USA) across the deformation front on the lower continental slope off northwest Oregon. The fold-thrust belt of uplifted abyssal strata of Pliocene and early Pleistocene age is underplated by an eastward thickening accretionary prism of late Oligocene(?) and Miocene age. The top of the subducting Juan de Fuca can be traced from the base of the slope eastward for about 55 km (35 mi). Symbols: Qu, undifferentiated Quaternary sediments; Tp -Q, Tertiary-Quaternary undifferentiated; Tp, Pliocene strata; Tmu, upper Miocene strata; Tmv, Miocene oceanic basalt.

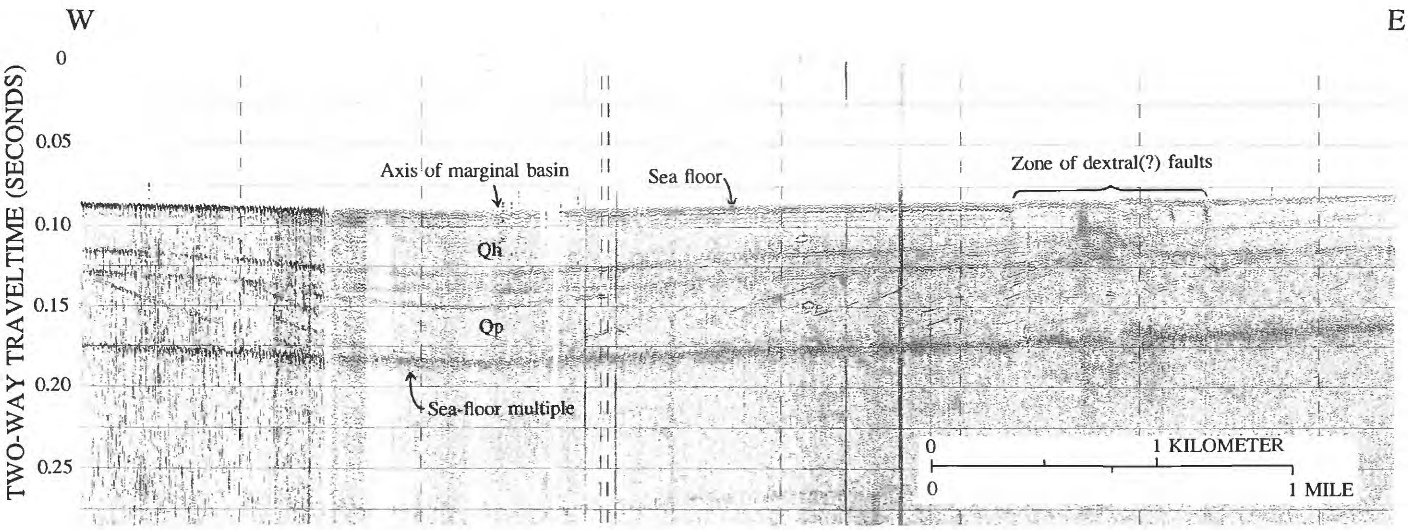

Figure 10. High-resolution seismic-reflection profile extending westward just south of Newport, Oregon across the axis of the deep marginal basin on the inner shelf. Note the stacked unconformities along the basin axis due to episodic periods of downwarping. The seafloor also appears to be downwarped, indicating a present transpressional regime. A 3.5-km (2.2 mi) - wide zone of faulting is present along the eastern margin of the basin. These north-trending faults are interpreted to be dextral strike-slip faults along which the northeast to southwest transpression was released, perhaps resulting in the small magnitude earthquakes along this segment of the Oregon coast.

blocks and the fact that they have been uplifted above the level of the surrounding flat erosion surface, which most likely was beveled during the late Pleistocene low stand of sea level, all point to recent uplift and attendant tensional faulting.

Multichannel seismic-reflection profiles off southern Vancouver Island are similar to those off Oregon, in that sediments of the Cascadia basin have been uplifted as much as 600 m (1,970 ft). The seaward segment of a profile (fig. 12) that crosses the base of the slope clearly shows a major northeast-dipping thrust fault (fault A) that uplifts virtually the entire section of strata above upper Miocene oceanic crust. Fault A is overlain by a small basin which contains about 120 m (400 ft) of Holocene and upper Pleistocene(?) sediments. The 120 m (400 ft) section of sediment that overlies thrust fault A indicates that this fault has been inactive since late(?) Pleistocene time. Thrust fault B, which lies seaward (southwest) of the principal thrust fault A, also is overlain by a thick sequence of late Pleistocene and Holocene sediments. As the imbricate thrust faults along the outer shelf and slope of Oregon and Washington have migrated seaward with time, the next major displacement may be along fault B. This relation of late Pleistocene sediments deposited over the trace of thrust fault A in figure 12 and folded or tilted unconformities in lower slope basins (fig. 6) suggests episodic rather than continuous underthrusting at the base of the continental slope.

ONSHORE FEATURES

Major landslides such as those in the Olympic Mountains that divided ancient Lake Crescent into the present two lakes--Lake Crescent on the west and Lake Sutherland on the east (Brown and others, 1960; Tabor, 1975)--may have been initiated by a seismic event

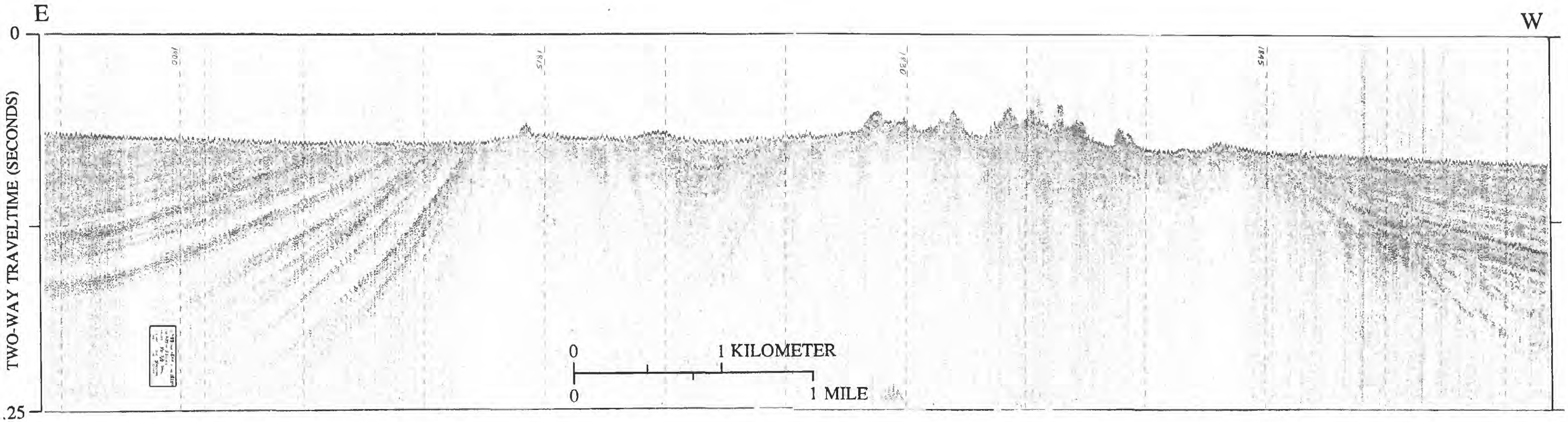

Figure 11. West-trending high-resolution seismic-reflection profile across the inner shelf of northwest Oregon, just south of the Columbia River. The broad diapiric fold in the western part of the profile is capped by pinnacle-like features that rise 5 to 15 m (16-50 ft) above the sea floor. These recent features are considered to be horst and graben structures resulting from extension across the crest of the fold. The flat erosion surface that truncates dipping early(?) Pleistocene strata was most likely formed during the late Pleistocene low stand of sea level.

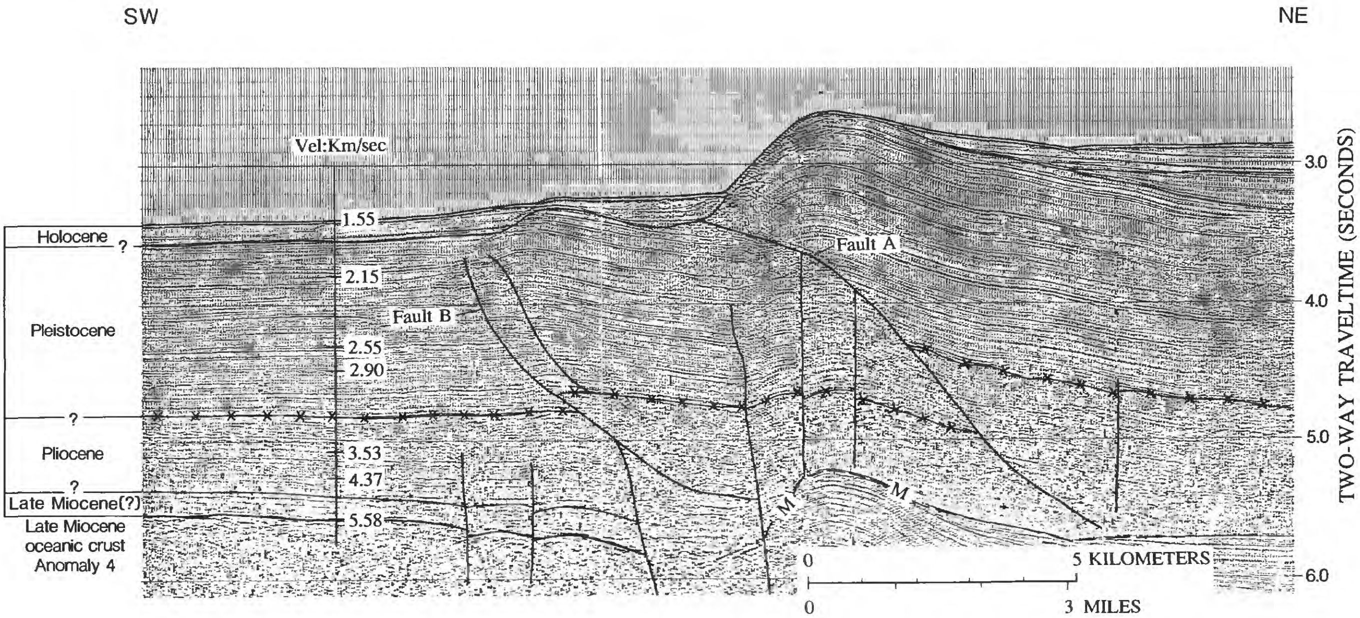

Figure 12. Twenty-four channel seismic-reflection profile, USGS line 80-7, across the abyssal plain and lower slope off southwestern Vancouver Island, B.C. Landward-dipping thrust fault A has folded and uplifted Pleistocene and Pliocene abyssal sediments approximately 700 m (2,300 ft) thick. This fault apparently has been inactive during the Holocene, because deposits of Holocene age in the small basin south of the thrust fold are not offset by fault A. Fault B, southwest of fault A, indicates that the deformation front at the base of the slope is migrating seaward. Velocities in km/sec are based on sonobuoy refraction data. M, indicates sea-floor multiple. Vertical exaggeration is approximately 3:1, based on sea-water velocity.

during late Holocene time. A Quilleute Indian legend purports that during a great battle between the Clallam and Quilleute Indians, Mount Storm King (on the south side of Lake Crescent) became angry and took a great piece of rock from his crest and hurled it down the valley, killing all who were fighting (Tabor, 1975). Although the debris that forms the older and major landslide came largely from the north, a large slide also originated from the ridge just east of Mount Storm King (Brown and others, 1960). The youthful nature of the older landslide, which is indicated by the lack of a thick soil zone on the landslide debris and hummocky topography with closed depressions that contain little recent fill, suggests that the older slide may have occurred relatively soon after the melting of the ice lobe that occupied the Lake Crescent-Lake Sutherland valley. Studies on the Lake Crescent landslide dam by Logan and Schuster (1991), support a Holocene age for the landslide. They report a 500-550 year old tree growing on rocks that form the dam. A submerged tree on the west side of the older landslide, apparently in an upright (growth) position in Lake Crescent, has a ^{14}C age of 350 years (Snavely, 1987). However, this tree was probably transported into the lake by the younger slide, perhaps the one witnessed by the Indians.

Pleistocene and Holocene faults are present along the coastal zone and on the continental shelf. In the western part of the Olympic Peninsula, late Pleistocene glacial drift is sheared and tectonically interleaved with siltstone beds of Eocene age (Snavely, 1983). North of Ozette Lake, a Holocene soil zone on upper Pleistocene outwash gravels is offset as much as 2 m (6.5 ft). To the southwest, on the continental shelf off Grays Harbor, Washington, sea floor sediments are offset about 7 m (23 ft) by a "trap-door" type of fault (Snavely and others, 1977). On the inner shelf and coastal zone of central Oregon, a 75-km (47 mi) -long north-trending zone of steeply dipping normal faults offsets Holocene(?) sediments (Snavely and others, 1980b); onshore these faults offset upper Pleistocene marine-terrace deposits (Snavely and others, 1976a, b). These faults are downthrown to the east toward the uplifted Coast Range rather than toward the basin, as one would expect for seaward-verging thrust faults or gravity faults. Several earthquakes with modified Mercalli intensities of III to IV have occurred in the vicinity of Newport (Berg and Baker, 1963) and may have been generated by movement along faults within this zone.

EARTHQUAKE POTENTIAL

Although present seismic activity is low along the continental margin of Oregon and Washington, this region lies along a major subduction zone where the Juan de Fuca and North American plates are converging at 3.5 cm (1.4 in. per year) (Riddihough, 1977). In most subduction zones, episodic strain release has generated large earthquakes (Plafker, 1972; Kanamori, 1977; Heaton and Kanamori, 1984), but the absence of a well-defined megathrust along the Washington and Oregon convergent margin has perplexed geologists and seismologists. They have proposed several models to account for the seismically quiescent plate boundary:

(1) Convergence has ceased between the Juan de Fuca and North American plates.

(2) Convergence is occurring along the plate boundaries, but is aseismic because a young, warm, plastic oceanic crust is being subducted with ductile rather than brittle deformation of the plate boundary.

(3) The Juan de Fuca and North American plates presently are strongly coupled forming a seismic gap along this segment of the Northeast Pacific.

Geodetic measurements by Savage and others (1981) indicate that crustal strain is accumulating in the Puget Sound area and has an average principal direction of contraction of N 71° E ± 6°. This direction of contraction is in general agreement with the N 50° E direction of relative motion between the Juan de Fuca and North American plates. It also agrees closely with the direction of tectonic transport during the late middle Miocene period of plate convergence, as deduced from drag-folds in the upper plate of the Ozette thrust fault in the northwesternmost part of the Olympic Peninsula (Tm, fig. 3; Snavely and others, 1986).

Landward tilting in the Oregon and Washington Coast Range and the Olympic Peninsula has been documented by using tide gauges and by geodetic leveling of uplifted marine terraces (Adams, 1984). This landward tilt and crustal shortening shown by thrust faults and folds on the outer shelf and slope of Oregon (Kulm and Fowler, 1974; Seely, 1977; Snavely and others, 1980b; Snavely, 1987) and on the slope, continental shelf, and coastal zone of Washington (Silver, 1972; Carson, 1977; Snavely and Wagner, 1982; Rau, 1975, 1979; Snavely and others, 1986; Wells, 1989), is characteristic of many other subduction zones where major thrust earthquakes have occurred.

Detailed stratigraphic studies of buried late Holocene estuarine deposits in westernmost Washington led Atwater (1987) to conclude that coseismic subsidence is responsible for their burial. At least six episodes of coseismic subsidence may have occurred in the last 7,000 years. Individual episodes of subsidence extended for many tens of kilometers along the coast and at least 30 km (18.6 mi) inland and implies large Cascadia subduction zone earthquakes. Similar investigations of coastal salt marshes in Oregon by Peterson and Darienzo (1988) have established late Holocene episodic tectonic subsidence that is interpreted as evidence of abrupt strain release and intervening gradual strain accumulation along the southern Cascadia margin during the last 3,500 years.

The episodic subsidence of coastal lowlands and the evidence for episodic thrust faulting along the deformation front may both reflect intermittent coupling between the Juan de Fuca and North American plates. Presently, the thrust interface may be strongly coupled and elastic strain may be accumulating across the continental margin (Heaton and Kanamori, 1984). Based upon their interpretation of earthquake focal mechanism data, Weaver and Smith (1983) also concluded that the subduction zone is locked. Since there is no historic record of large shallow earthquakes along the subduction zone, a 900-km (560 mi) -long seismic gap seems to be present along the subduction zone off Oregon and Washington--the most remarkable gap to be found in the Circum-Pacific seismic belt (Heaton and Kanamori, 1984). Despite the fact that present-day seismic activity is low, the potential for a major subduction-type earthquake cannot be discounted.

ACKNOWLEDGMENTS

We thank Exxon Company, U.S.A. for generously making available their seismic-reflection profile off the mouth of the Columbia River, as this profile clearly images the structure of this segment of the Oregon continental margin. Weldon W. Rau and David Bukry provided the biostratigraphic framework for the Tertiary sequence that is the basis for timing of most geologic events. John G. Vedder, Alan R. Niem, and Timothy Walsh reviewed the manuscript and offered suggestions that improved its quality. The writers are particularly grateful to Diane L. Minasian who drafted the illustrations and critically reviewed the manuscript.

REFERENCES CITED

Adams, John, 1984, Active deformation of the Pacific northwest continental margin: Tectonics, v. 3, no. 4, p. 449-472.

Addicott, W.O., 1976, Molluscan paleontology of the lower Miocene Clallam Formation, northwestern Washington: U.S. Geological Survey Professional Paper 976, 44 p.

Allen, J.E., and Baldwin, E.M., 1944, Geology and coal resources of the Coos Bay quadrangle, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 27, 160 p.

Armentrout, J.M., 1980, Cenozoic stratigraphy of Coos Bay and Cape Blanco, southwestern Oregon, *in* Oles, K.F., Johnson, J.G., Niem, A.R. and Niem, W.A., eds., Geologic field trips in western Oregon and southwestern Washington: Oregon Department of Geology and Mineral Industries Bulletin 101, p. 175-216.

Arnold, Ralph, 1906, Geological reconnaissance of the coast of the Olympic Peninsula, Washington: Geological Society of America Bulletin, v. 17, p. 451-468.

Atwater, B.F., 1987, Evidence for great Holocene earthquake along the outer coast of Washington State: Science, v. 236, p. 942-944.

Baldwin, E.M., 1974, Eocene stratigraphy of southwestern Oregon: Oregon Department of Geology and Mineral Industries Bulletin 83, 40 p.

Baldwin, E.M., Brown, R.D., Jr., Gair, J.E., and Pease, M.H., Jr., 1955, Geology of the Sheridan and McMinnville quadrangles, Oregon: U.S. Geological Survey Oil and Gas Investigations Map OM-155, scale 1:62,500.

Beeson, M.H., Perttu, R., and Perttu, J., 1979, The origin of the Miocene basalts of coastal Oregon and Washington: An alternative hypothesis: Oregon Geology, v. 41, p. 159-166.

Berg, J.W., Jr., and Baker, C.D., 1963, Oregon earthquakes, 1841 through 1958: Seismological Society of America Bulletin, v. 53, p. 95-108.

Blake, M.C., Jr., 1984, Tectonostratigraphic terranes in southwestern Oregon *in* Nilsen, T.H., ed., Geology of the Upper Cretaceous Hornbrook Formation, Oregon and California: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 42, p. 159-165.

Blake, M.C., and Jayko, A.S., 1986, Tectonic evolution of northwest California and southwest Oregon: Geological Society of France Bulletin, v. 6, p. 921-930.

Bond, K.R., and Zeitz, I., 1987, Composite magnetic anomaly map of the conterminous United States west of 96° longitude: U.S. Geological Survey Geophysical Investigation Map GP-977, scale 1:2,500,000.

Brandon, M. T., and Calderwood, A. R., 1990, High-pressure metamorphism and uplift of the Olympic subduction complex: Geology, v. 18, no. 12, p. 1252-1255.

Brandon, M.T., Miller, D.S., and Vance, J.A., 1988, Fission-track dates for initiation and uplift of the Cenozoic subduction complex of the Olympic Mountains, northwest Washington: Geological Society of America Abstracts with Programs, v. 20, p. 145.

Brown, R.D., Jr., Snavely, P.D., Jr., and Gower, H.D., 1956, Lyre Formation (redefinition), northern part of Olympic Peninsula, Washington: American Association of Petroleum Geologists Bulletin, v. 40, p. 94-107.

Brown, R.D., Jr., Gower, H.D., and Snavely, P.D., Jr., 1960, Geology of the Lake Crescent-Port Angeles area, Washington: U.S. Geological Survey Oil and Gas Investigation Map QM-203, scale 1:62,500.

Bukry, David, and Snavely, P. D., Jr., 1988, Coccolith zonation for Paleogene strata in the Oregon Coast Range, *in* Filewicz, M.V., and Squires, R.L., eds., Paleogene Stratigraphy, West Coast of North America: Pacific Section, Society of Economic Paleontologists and Mineralogists, West Coast Paleogene Symposium, v. 58, p. 251-263.

Byrne, J.V., Fowler, G.A., and Maloney, N.M., 1966, Uplift of the continental margin and possible continental accretion off Oregon: Science, v. 154, no. 3757, p. 1654-1656.

Cady, W.M., 1975, Tectonic setting of the Tertiary volcanic rocks of the Olympic Peninsula, Washington: U.S. Geological Survey Journal of Research, v. 3, p. 573-582.

Carlson, P.R., and Nelson, C.H., 1987, Marine geology and resource potential of Cascadia basin, *in* Scholl, D.W., Grantz, Arthur, and Vedder, J.G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins--Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 6, p. 523-535.

Carson, Bobb, 1977, Tectonically induced deformation of deep-sea sediments off Washington and northern Oregon: Mechanical consolidation: Marine Geology, v. 24, p. 289-307.

Carson, Bobb, Yan, Jennwei, Myers, P.B., Jr., and Barnard, W.D., 1974, Initial deep-sea sediment deformation at the base of the Washington continental slope: a response to subduction: Geology, v. 2, no. 11, p. 561-564.

Chan, M.A., and Dott, R.H., Jr., 1983, Shelf and deep-sea sedimentation in Eocene forearc basin, western Oregon-fan or non-fan?: American Association of Petroleum Geologists Bulletin, v. 67, p. 2100-2116.

Clapp, C.H., 1917, Sooke and Duncan map area, Vancouver Island, British Columbia: Geological Survey of Canada Memoir 96, 445 p.

Clarke, Samuel H., Jr., 1991, Geology of the Eel River Basin and adjacent region: implications for Late Cenozoic tectonics of the southern Cascadia subduction zone and Mendocino Triple Junction: American Association of Petroleum Geologists Bulletin [in press].

Clarke, S.H., Jr., Field, M.F., and Hirozawa, C.A., 1981, Reconnaissance geology and geologic hazards of offshore Coos Bay basin central Oregon continental margin: U.S. Geological Survey Open-File Report 81-898, 84 p.

Clowes, R.M., Brandon, M.T., Green, A.R., Yorath, C.J., Sutherland Brown, A., Kanasewich, E.R., and Spencer, C., 1987, Lithoprobe-Southern Vancouver Island-Cenozoic subduction complex imaged by deep seismic reflections: Canadian Journal of Earth Sciences, v. 24, no. 1, p. 31-51.

Cooper, M.D., 1981, Sedimentation, stratigraphy, and facies variations of the lower to middle Miocene Astoria Formation in Oregon: Corvallis, Or., Oregon State University unpublished Ph.D. dissertation, 524 p.

Davis, A.S., and Plafker, George, 1986, Eocene basalts from the Yakutat terrane: Evidence for the origin of an accreting terrane in southern Alaska: Geology, v. 14, p. 963-966.

Davis, E.E., and Hyndman, R.D., 1989, Accretion and recent deformation of sediments along the northern Cascadia subduction zone: Geological Society of America Bulletin, v. 101, p. 1465-1480.

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran collage, central British Columbia to central California, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists Special Publication, p. 1-32.

Dott, R.H., Jr., 1966, Eocene deltaic sedimentation at Coos Bay, Oregon: Journal of Geology, v. 74, p. 373-420.

Duncan, R.A., 1982, A captured island chain in the Coast Range of Oregon and Washington: Journal of Geophysical Research, v. 87, p. 10,827-10,837.

Easterbrook, D.J., 1969, Pleistocene chronology of the Puget Lowland and San Juan Islands, Washington: Geological Society of America Bulletin, v. 80, p. 2273-2286.

Engebretson, D.C., Cox, A., and Gordon, R.G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, 59 p.
Engebretson, D.C., Cox, A., and Thompson, G.A., 1984, Correlation of plate motions with continental tectonics: Laramide to Basin-Range: Tectonics, v. 3, no. 2 p. 115-119.
England, P.C., and Wells, R.E., 1991, Neogene rotations and continuum deformation of the Pacific Northwest convergent margin: Geology [in press].
Ewing, T.E., 1980, Paleogene tectonic evolution of the Pacific Northwest: Journal of Geology, v. 88, p. 619-638.
Fairchild, L.H., and Cowan, D.S., 1982, Structure, petrology, and tectonic history of the Leech River complex northwest of Victoria, Vancouver Island: Canadian Journal of Earth Sciences, v. 19, no. 9, p. 1817-1835.
Goodwin, C.J., 1973, Stratigraphy and sedimentation of the Yaquina Formation, Lincoln County, Oregon: Corvallis, Or., Oregon State University unpublished M.S. thesis, 121 p.
Gower, H.D., 1960, Geology of the Pysht quadrangle, Washington: U.S. Geological Survey Geologic Quadrangle Map GQ-129, scale 1:62,500.
Haq, Bilal U., Hardenbol, Jan, and Vail, Peter R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156-1167.
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.
Heller, P.L., Peterman, Z.E., O'Neil, J.R., and Shafiqullah, Muhammad, 1985, Isotopic provenance of sandstones from the Eocene Tyee Formation, Oregon Coast Range: Geological Society of America Bulletin, v. 96, p. 770-780.
Heller, P.L., and Ryberg, P.T., 1983, Sedimentary record of subduction to forearc transition in the rotated Eocene basin of western Oregon: Geology, v. 11, p. 380-383.
Johnson, S.Y., 1984, Evidence for a margin-truncating transcurrent fault (pre-late Eocene) in western Washington: Geology, v. 12, no. 9, p. 538-541.
Kanamori, H., 1977, Seismic and aseismic slip along subduction zones and their tectonic implications, *in* Talwani, M., and Pittman, W.C., III, eds., Island arcs, deep sea trenches and back-arc basins, Washington, D.C., Maurice Ewing Series 1: American Geophysical Union, p. 173-174.
Kulm, L.D., and Fowler, G.A., 1974, Oregon continental margin model, *in* Burk, C.A., and Drake, C.L., eds., The geology of continental margins: New York, Springer-Verlag, p. 261-283.
Livingston, V.E., Jr., 1966, Geology and mineral resources of the Kelso-Cathlamet area, Cowlitz and Wahkiakum Counties, Washington: Washington Division of Mines and Geology Bulletin 54, 110 p.
Logan, R.L., and Schuster, R.L., 1991, Lakes divided: the origin of Lake Crescent and Lake Sutherland, Clallam County, Washington: Washington Geology (formerly Washington Geologic Newsletter), v. 19, no. 1, p. 38-42.
Lovell, J.P.B., 1969, Tyee Formation--undeformed turbidites and their lateral equivalents, mineralogy, and paleogeography: Geological Society of America Bulletin, v. 80, p. 9-22.
Ludwin, R.S., Weaver, C.S., and Crosson, R.R., 1991, Seismicity of Oregon and Washington, *in* Slemmons, D.B., Engdahal, E.R., Blackwell, D., and Schwartz, D., eds, Neotectonics of North America: Geological Society of America DNAG (Decade of North America) volume [in press]..
MacLeod, N.S., 1969, Geology and igneous petrology of the Saddleback area, central Oregon Coast Range: Santa Barbara, Ca., University of California, unpublished Ph.D. dissertation, 205 p.

MacLeod, N.S., and Snavely, P.D., Jr., 1973, Volcanic and intrusive rocks of the central part of the Oregon Coast Range: Oregon Department of Geology and Mineral Industries Bulletin, no. 77, p. 47-74.
MacLeod, N.S., Tiffin, D.L., Snavely, P.D., Jr., and Currie, R.G., 1977, Geologic interpretation of magnetic and gravity anomalies in the Strait of Juan de Fuca, U.S.-Canada: Canadian Journal of Earth Sciences, v. 14, no. 2, p. 223-238.
Magill, J.R., Cox, A., and Duncan, R., 1981, Tillamook Volcanic Series: Further evidence for tectonic rotation of the Oregon Coast Range: Journal of Geophysical Research, v. 86, p. 2953-2970.
McLellan, R.D., 1927, The geology of the San Juan Islands: Washington University Publications Geology, v. 3, 180 p.
Molenaar, C.M., 1985, Depositional relationships of the Umpqua and Tyee Formations (Eocene), Southwestern Oregon: American Association of Petroleum Geologists Bulletin, v. 69, no. 8, p. 1217-1229.
Muller, J.E., 1977, Evolution of the Pacific margin, Vancouver Island, and adjacent regions: Canadian Journal of Earth Sciences, v. 14, no. 9, p. 2062-2085.
Niem, A.R., and Niem, W.A., 1985, Oil and gas investigation of the Astoria Basin, Clatsop and northernmost Tillamook counties, northwest Oregon: Oregon Department of Geology and Mineral Industries Oil and Gas Investigation 14, 8 p.
_____1990, Geology and oil, gas, and coal resources, southern Tyee Basin, southern Coast Range, Oregon: State of Oregon Department of Geology and Mineral Industries, Open-File Report 0-89-3, 3 plates, 11 tables.
Niem, A. R., Snavely, P. D., Jr., Chen, Y., and Niem, W.A., 1989, Jansen Creek Member of the Makah Formation - A major Oligocene submarine landslide or slump deposit from the Vancouver shelf in the Juan de Fuca deep marginal basin, NW Olympic Peninsula, Washington [abs.]: Geological Society of America, Cordilleran Section, 85th, Rocky Mountain Section, 42nd, Spokane, Washington, 1989, Abstracts with Programs, v. 21, no. 5, p. 123.
Niem, A.R., Snavely, P.D., Jr., and Niem, W.A., 1990, Onshore-offshore geologic cross section from the Mist Gas field, northern Oregon Coast Range, to the northwest Oregon continental shelf and slope: Oregon Department of Geology and Mineral Industries Continental Margin Transect OGI-17, 46 p., 1 plate.
Pease, M.H., and Hoover, L., 1957, Geology of the Doty-Minot Peak area, Washington: U.S. Geological Survey Oil and Gas Investigations Map OM-188, scale 1:62,500.
Peterson, C.D., and Darienzo, M.E., 1988, Episodic tectonic subsidence of late Holocene salt marshes in Oregon: clear evidence of abrupt strain release and gradual strain accumulation in the southern Cascadia margin during the last 3,500 years: U.S. Geological Survey Open-File Report 88-541, p. 110-113.
Plafker, George, 1972, Alaskan earthquake of 1964 and Chilean earthquake of 1960--Implications for arc tectonics: Journal of Geophysical Research, v. 77, p. 901-925.
Rau, W.W., 1970, Foraminifera, stratigraphy and paleoecology of the Quinault Formation, Point Grenville-Raft River coastal area, Washington: Washington Division of Mines and Geology Bulletin 62, 40 p.
_____1975, Geologic map of the Destruction Island and Taholah quadrangles, Washington: Washington Division of Geology and Earth Resources, Geologic Map GM-13, scale 1:62,500.
_____1979, Geologic map in the vicinity of the lower Bogachiel and Hoh River Valleys, and the Washington Coast: Washington Division of Geology and Earth Resources Geology Map GM-24, scale 1:62,500.
Riddihough, R.P., 1977, A model for recent plate interactions off Canada's west coast: Canadian Journal of Earth Science, v. 14, p. 384-396.
Russell, I.C., 1900, Geology of the Cascade Mountains in northern Washington: U.S. Geological Survey Annual Report 20, pt. 2, p. 83-210.

Ryberg, P.T., 1984, Sedimentation, structure and tectonics of the Umpqua Group (Paleocene to early Eocene), southwestern Oregon: Tucson, Az., University of Arizona, Ph.D. dissertation, 280 p.

Savage, J.C., Lisowki, M., and Prescott, W.H., 1981, Geodetic strain measurements in Washington: Journal of Geophysical Research, v. 86, p. 4929-4940.

Scholl, D.W., von Huene, Roland, Vallier, T.L., and Howell, D.G., 1980, Sedimentary masses and concepts about tectonic processes at underthrust ocean margins: Geology, v. 8, p. 564-568.

Shouldice, D.H., 1971, Geology of the western Canadian continental shelf: Canadian Petroleum Geology Bulletin, v. 19, no. 2, p. 405-436.

Seely, D.R., 1977, The significance of landward vergence and oblique structural trends on trench inner slopes, *in* Talwani, M. and Pitman, W.C., III, eds., Island Arcs, Deep Sea Trenches and Back-Arc Basins, Maurice Ewing Series 1: American Geophysical Union, p. 187-198.

Silver, E.A., 1972, Pleistocene tectonic accretion of the continental slope off Washington: Marine Geology, v. 13, p. 239-249.

Snavely, P.D., Jr., 1948, Coquille Formation in the Nestucca Bay quadrangle, Oregon: Geological Society of Oregon, Geological News Letter, v. 14, no. 2, p. 11-12.

_____1983, Peripheral rocks—Tertiary geology of the northwestern part of the Olympic Peninsula, Washington, *in* Muller, J.E., Snavely, P.D., Jr., and Tabor, R.W., eds., The Tertiary Olympic terrane, southwest Vancouver Island and northwest Washington: Geological Association of Canada, Mineralogical Association of Canada, Canadian Geophysical Union Field Trip Guidebook, Trip 12, 59 p.

_____1984, Sixty million years of growth along the Oregon continental margin, *in* Clarke, S.H., ed., U.S. Geological Survey, Highlights in marine research: U.S. Geological Survey Circular 938, p. 9-18.

_____1987, Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon-Washington Continental Margin, *in* Scholl, D.W., Grantz, A., and Vedder, J.G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins--Beaufort Sea to Baja California: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 305-335.

_____1991, The Salmon River Formation--a lower Eocene sequence in the Central Oregon Coast Range: U.S. Geological Survey Bulletin 1935, p. 1-4.

Snavely, P.D., Jr., Brown, R.D., Jr., Roberts, A.E., and Rau, W.W., 1958, Geology and coal resources of the Centralia-Chehalis district, Washington: U.S. Geological Survey Bulletin 1053, 159 p.

Snavely, P.D. Jr., and Kvenvolden, K.A., 1989, Chapter A, Geology and hydrocarbon potential, Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington: U.S. Geological Survey Bulletin 1892 A-C, p. 1-17.

Snavely, P.D., Jr., and MacLeod, N.S., 1974, Yachats Basalt—An upper Eocene differentiated volcanic sequence in the Oregon Coast Range: U.S. Geological Survey Journal of Research, v. 2, no. 4, p. 395-403.

Snavely, P. D., Jr., MacLeod, N. S., and Minasian, D. L., 1990a, Preliminary map of the Nestucca Bay Quadrangle, Tillamook County, Oregon: U.S. Geological Survey Open-File Report 90-202, scale 1:24,000.

_____1990b, Preliminary geologic map of the Neskowin quadrangle, Tillamook County, Oregon: U.S. Geological Survey Open-File Report 90-413, scale 1:24,000.

Snavely, P.D., Jr., MacLeod, N.S., Niem, A.R., and Minasian, D.L., 1986, Geologic map of Cape Flattery area, Northwestern Olympic Peninsula, Washington: U.S. Geological Survey Open-File Report 86-344B, scale 1:48,000.

Snavely, P.D., MacLeod, N.S., and Rau, W.W., 1970, Summary of the Tillamook area, northern Oregon Coast Range: U.S. Geological Survey Professional Paper 650-A, p. A47.
Snavely, P.D., Jr., MacLeod, N.S., Rau, W.W., Addicott, W.O., and Pearl, J.E., 1975, Alsea Formation—An Oligocene marine sedimentary sequence in the Oregon Coast Range: U.S. Geological Survey Bulletin 1395-F, 21 p.
Snavely, P.D., Jr., MacLeod, N. S. and Wagner, H.C., 1968, Tholeiitic and alkalic basalts of the Eocene Siletz River Volcanics, Oregon Coast Range: American Journal of Science, v. 266, p. 454-481.
_____1973, Miocene tholeiitic basalts of coastal Oregon and Washington and their relations to coeval basalts of the Columbia Plateau: Geological Society of America Bulletin, v. 84, no. 2, p. 387-424.
Snavely P.D., Jr., MacLeod, N.S., Wagner, H.C., and Rau, W.W., 1976a, Geologic map of the Cape Foulweather and Euchre Mountain quadrangles: U.S. Geological Survey Miscellaneous Investigations Series Map I-868, scale 1:62,500.
_____1976b, Geologic map of the Yaquina and Toledo quadrangles: U.S. Geological Survey Miscellaneous Investigations Series Map I-867, scale 1:62,500.
_____1976c, Geologic map of the Waldport and Tidewater quadrangles, Lincoln, Lane, and Benton Counties, Oregon: U.S. Geological Survey Miscellaneous Investigations Series Map I-866, scale 1:62,500.
Snavely, P.D., Jr., and McClellan, P.H., 1987, Preliminary geologic interpretation of USGS *S.P. Lee* seismic-reflection profile WO 76-7 on the continental shelf and upper slope, northwestern Oregon: U.S. Geological Survey Open-File Report 87-612, 12 p.
Snavely, P.D., Jr., Niem, A.R., and MacLeod, N.S., 1989, Geology of the coastal area between Cape Flattery and Cape Alava, northwest Washington: U.S. Geological Survey Open-File Report 89-141.
Snavely, P.D., Jr., Niem, A.R., MacLeod, N.S., Pearl, J.E., and Rau, W.W., 1980a, Makah Formation—A deep marginal basin sedimentary sequence of upper Eocene and Oligocene age in the northwestern Olympic Peninsula, Washington: U.S. Geological Survey Professional Paper 1162-B, 28 p.
Snavely, P.D., Jr., Niem, A.R., and Pearl, J.E., 1978, Twin River Group (upper Eocene to lower Miocene)—Defined to include the Hoko River, Makah, and Pysht Formations, Clallam County Washington: U.S. Geological Survey Bulletin 1457-A, p. A111-A120.
Snavely, P.D., Jr., Pearl, J.E., and Lander, D.L., 1977, Interim report on petroleum resources potential and geologic hazards in the outer continental shelf--Oregon and Washington Tertiary province: U.S. Geological Survey Open-File Report 77-282, 64 p.
Snavely, P.D., Jr., and Vokes, H.E., 1949, Geology of the coastal area between Cape Kiwanda and Cape Foulweather, Oregon: U.S. Geological Survey Oil and Gas Investigations Preliminary Map 97.
Snavely, P.D., Jr., von Huene, Roland, and Miller, J., 1987, The central Oregon margin Lines WO76-4, *in* von Huene, R. (ed.), Seismic images of convergent margin tectonic structure: American Association of Petroleum Geologists Studies in Geology No. 26, p. 24-27.
Snavely, P.D., Jr., and Wagner, H.C., 1963, Tertiary geologic history of western Oregon and Washington: Washington Division of Mines and Geology Report of Investigations 22, 25 p.
_____1980, Generalized isopach map of Tertiary sedimentary rocks, western Oregon and Washington and adjacent continental margin: U.S. Geological Survey Open-File Report 80-889, scale 1:1,000,000.

_____1981, Geologic cross section across the continental margin off Cape Flattery, Washington and Vancouver Island, British Columbia: U.S. Geological Survey Open-File Report 81-0978, 6 p.

_____1982, Geologic cross section across the continental margin of southwestern Washington: U.S. Geological Survey Open-File Report 82-459, 10 p.

Snavely, P.D., Jr., Wagner, H.C., and Lander, D.L., 1980b, Geological cross section of the central Oregon continental margin: Geological Society of America Map and Chart Series MC-28J, scale 1:250,000.

_____1985, Land-sea geologic cross section of the southern Oregon continental margin: U.S. Geological Survey Miscellaneous Investigation Series Map-1463.

Snavely, P.D., Jr., Wagner, H.C., and MacLeod, N.S., 1964, Rhythmic-bedded eugeosynclinal deposits of the Tyee Formation--Oregon Coast Range, *in* the Symposium on Cyclic Sedimentation: Kansas Geological Survey Bulletin 169, p. 461-480.

Snavely, P.D., Jr., Wagner, H.C., and Rau, W.W., 1982, Sections showing biostratigraphy and correlation of Tertiary rocks penetrated in wells drilled on the southern Oregon continental margin: U.S. Geological Survey Miscellaneous Field Studies Map MF-1482, 1 sheet.

Snavely, P.D., Jr., and Wells, R.E., 1984, Tertiary volcanic and intrusive rocks on the Oregon and Washington continental shelf: U.S. Geological Survey Open-File Report 84-282, 17 p.

Spence, William, 1989, Stress origins and earthquake potential in Cascadia: Journal of Geophysical Research, v. 94, no. B3, p. 3076-3088.

Stewart, R.J., 1974, Zeolite facies metamorphism of sandstone in the western Olympic Peninsula, Washington: Geological Society of America Bulletin, v. 85, no. 7, p. 1139-1142.

Tabor, R.W., 1975, Guide to the Geology of Olympic National Park: Seattle, Washington, University of Washington Press, 144 p.

Tabor, R.W., and Cady, W.M., 1978a, The structure of the Olympic Mountains, Washington—analysis of a subduction zone: U.S. Geological Survey Professional Paper 1033, 38 p.

_____1978b, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Map I-994, scale 1:125,000.

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

Tabor, R.W., Yeats, R.S., and Sorensen, M.L., 1972, Geologic map of the Mount Angeles Quadrangle Clallam and Jefferson Counties, Washington: U.S. Geological Survey Geologic Quadrangle Maps of the United States GQ-958, scale 1:62,500.

Tolan, T.L., and Reidel, S.P., 1989, Structure map of a portion of the Columbia River flood-basalt province, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, 1 sheet, scale 1:555,000.

Vokes, H.E., and Snavely, P.D., Jr., 1948, The age and relationships of the Eugene and Fisher Formations: Geological Society of the Oregon Country News Letter, v. 14, no. 5, p. 38-41.

Wagner, H.C., and Tomson, J.H., 1987, Geologic history and hazards geology within the Strait of Juan de Fuca: Washington Division of Geology and Earth Resources Open-File Report 87-1, 15 p., 7 pls.

Walsh, T.J., Korosec, M.A., Phillips, W.M., Logan, R.L., and Schasse, H.W., 1987, Geologic map of Washington—southwest quadrant: Washington State Department of Natural Resources Geologic Map GM-34, scale 1:250,000.

Warren, W.C., Grivetti, R.M., and Norbisrath, H., 1945, Geology of northwestern Oregon, west of Willamette River and north of latitude 45°15': U.S. Geological Survey Oil and Gas Investigations Preliminary Map OM-42, scale 1:145,728.

Weaver, C. S., and Smith, S. W., 1983, Regional tectonic and earthquake hazard implications of a crustal fault zone in southwestern Washington: Journal of Geophysical Research, v. 88, no. B12, p. 10,371-10,383.

Wells, R.E., 1981, Geologic map of the eastern Willapa hills, Cowlitz, Lewis, Pacific, and Wahkiakum Counties, Washington: U.S. Geological Survey Open-File Map 81-674, scale 1;62,500.

_____1989, Mechanisms of Cenozoic tectonic rotation, Pacific Northwest convergent margin, U.S.A., *in* Kiessel, C., and Laj, C., eds., Paleomagnetic rotations and continental deformation, "NATO Advanced Study Institute Series C, 254:" Kluwer Academic Publishers, p. 313-325.

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, no. B2, p. 1925-1947.

Wells, R.E., Engebretson, D.C., Snavely, P.D., Jr., and Coe, R.S., 1984, Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington: Tectonics, v. 3, no. 2, p. 275-294.

Wells, R.E., and Heller, Paul L., 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.

Wells, R.E., Niem, A.R., MacLeod, N.S., Snavely, P.D., Jr., and Niem, W.A., 1983, Preliminary geologic map of the west half of the Vancouver (Wash-Ore) 1°x2° sheet quadrangle Oregon: U.S. Geological Survey Open-File Report 83-591, scale 1:250,000.

Werner, K.S., Graven, E.P., Berkman, T.A., and Parker, M.J., 1991, Direction of maximum horizontal compression in western Oregon determined by borehole breakouts: Tectonics [in press].

Wolfe, J.A., Gower, H.D., and Vine, J.D., 1961, Age and correlation of the Puget Group, King County, Washington: U.S. Geological Survey Professional Paper 424-C, p. C230-232.

Zoback, M.L., and Zoback, M.D., 1989, Tectonic stress field of the continental United States, *in* Pakiser, L.C. and Mooney, W.D., eds., Geophysical framework of the United States: Geological Society of America Memoir, no. 172, p. 523-540.