U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

THE CENOZOIC GEOLOGY OF THE OREGON AND WASHINGTON COAST RANGE

and

ROAD LOG

for the

NORTHWEST PETROLEUM ASSOCIATION 9TH ANNUAL FIELD TRIP
CENOZOIC GEOLOGY OF COASTAL NORTHWEST OREGON

by

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Frontispiece — South side of Cape Kiwanda (lunch stop) consisting of massive to medium-bedded arkosic sandstone of the middle Miocene Astoria Formation. Here the Astoria sandstone unconformably overlies tuffaceous mudstone and fine-grained sandstone of the Oligocene Alsea Formation. The sea stack off Cape Kiwanda is a stock of middle Miocene Depoe Bay Basalt.

INTRODUCTION

Geologists at the U. S. Geological Survey have nearly completed geologic mapping of 7 fifteen minute quadrangles between Cascade Head and the Tillamook Highlands in the northern Oregon Coast Range (fig. 1). A major goal is to establish the basic stratigraphy and structure necessary to guide energy, mineral and geologic hazard investigations in northwest Oregon. The Highlands lie 30 km south of Oregon's only producing gas field at Mist, and they expose Eocene strata beneath shallow producing zones in nearshore marine sandstones of the Cowlitz Formation. Although repetitive basalt sequences dominate the Highlands stratigraphy, arkosic sandstone locally interfingers with Tillamook Volcanics and may indicate potential for deeper reservoirs to the northeast. Oil shales are exposed in the Yamhill Formation beneath the Tillamook Volcanics and may provide petroleum source-rock potential in the region.

Another important goal of this study is to determine the tectonic environment of the Eocene Tillamook Volcanics, which comprise a large part of the northern Oregon Coast Range. Paleomagnetic data indicate that the oceanic island-type tholeiitic basalt flows of the Tillamook Volcanics have undergone large (46°) clockwise rotations, and the basalts have been interpreted as seamounts that rotated during tectonic accretion to the continental margin (e.g., Simpson and Cox, 1977; Magill and others, 1981). Alternatively, the basalts may have erupted in situ, in a marginal rift basin that formed during a period of oblique subduction of offshore oceanic plates (Wells and others, 1984; Snavely, 1984, 1987; Clowes and others, 1987). Our mapping shows that the volcanic sequence in the Tillamook area can be correlated with the sequence in southwest Washington (previously considered a separate microplate) and can be tied to the continental shelf, thus supporting a local origin for the Tillamook Volcanics.

The map area also covers several coastal embayments, including Nehalem, Tillamook, and Netarts Bay (fig.1). Both Netarts and Nehalem Bay contain a record of episodic Holocene subsidence thought to represent coseismic deformation during large subduction zone earthquakes (e.g. Atwater, 1987; Peterson and Darienzo, 1988; Grant and Minor, 1991). Our mapping shows that Tillamook Bay and Netarts Bay are fault-bounded basins in which local structure also plays an important role in late Cenozoic, and possibly Quaternary deformation (Wells and others, 1992).

TECTONIC SETTING OF THE OREGON COAST RANGE

The convergent margin of Oregon and Washington consists of three major tectonic elements (fig. 2): 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

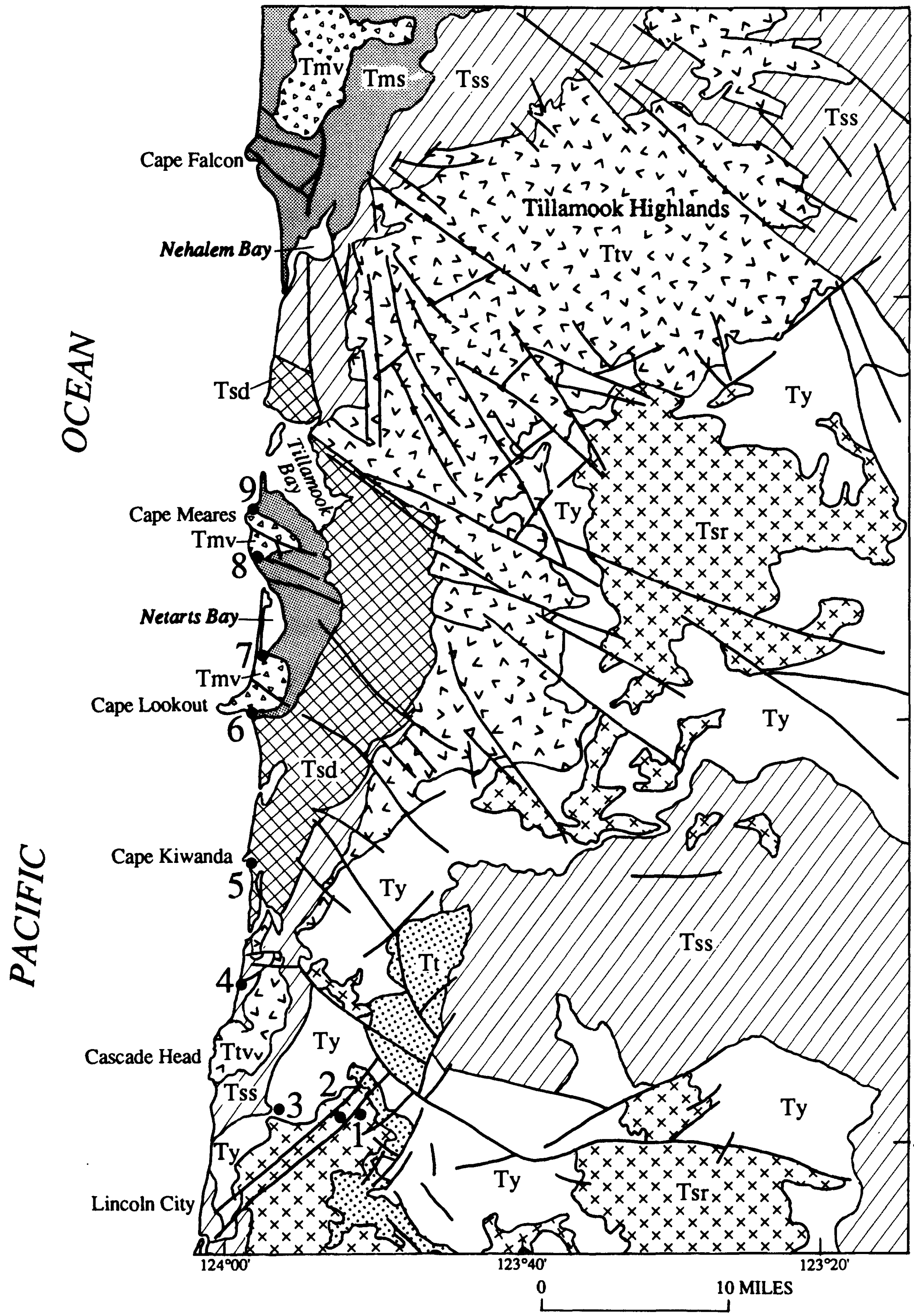


Figure 1.--Geologic map of the Central Oregon Coast Range showing field trip stops (modified from Walker and MacLeod, 1991)

Figure 1.--Continued

Explanation of Map Symbols

Tmv **Basalt flows and breccia (middle Miocene)**—Subaerial basalt and minor flow breccia; submarine palagonitic tuff and pillow complexes of the Columbia River Basalt Group (Swanson and others, 1979); locally includes invasive basalt flows. Flows locally grade laterally into subaqueous pillow-palagonite complexes and bedded palagonitic tuff and breccia. Occurs principally in the Willamette Valley from Salem north to the Columbia River, and in the northern Coast Range. Unit includes correlative Cape Foulweather and Depoe Bay Basalts in the Coast Range (Snavely and others, 1973; Swanson and others, 1979; Wells and others, 1983).

Tms **Marine sedimentary rocks (middle and lower Miocene)**—Fine- to medium-grained marine siltstone and sandstone that commonly contains tuff beds. Includes the Astoria Formation, which is mostly micaceous and carbonaceous sandstone, and locally contains calcareous concretions and sulfide nodules; foraminifers in formation are assigned to the Saucesian and Relizian Stages (Kleinpell, 1938; Rau, 1981) and molluscan fossils to the Newportian Stage of Addicott (1976, 1981). Also includes Nye Mudstone, which is massive to poorly bedded siltstone and mudstone; foraminiferal assemblages assigned to the Saucesian Stage (Kleinpell, 1938; Rau, 1981) and molluscan fauna to Pillarian(?) Stage (Armentrout, 1981)

Tsd **Sedimentary rocks (Oligocene and upper Eocene)**—Marine shale, siltstone, sandstone, and conglomerate, in places partly composed of tuffaceous and basaltic debris; interbeds of arkosic, glauconitic, and quartzose sandstone. Foraminifers are referable to the Refugian and Zemorrian Stages (Rau, 1981)

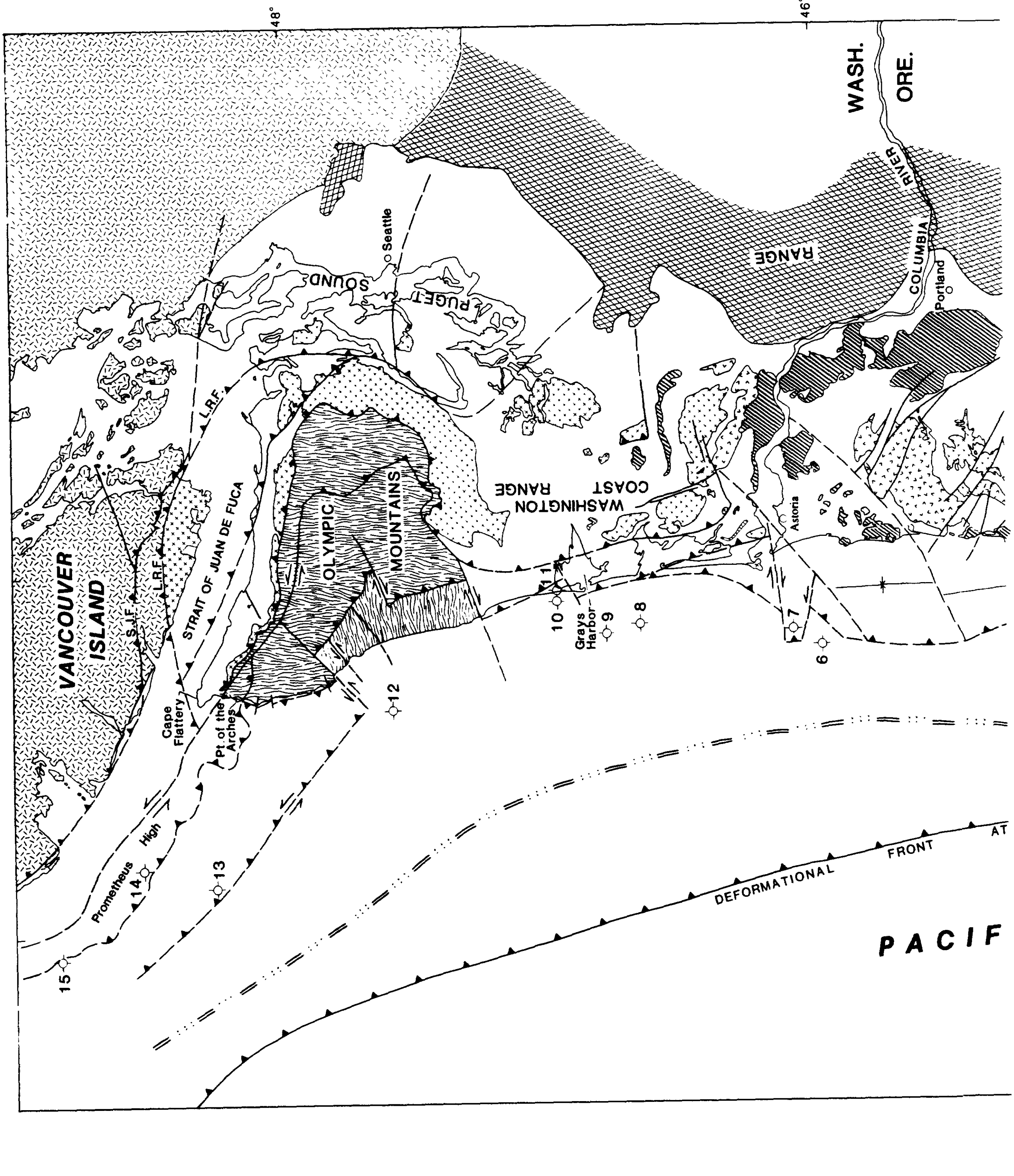
Ttv **Basalt flows and breccia, pillow lava and lapilli tuff (middle to late Eocene)**—Subaerial basaltic flows and breccia and submarine basaltic breccia, pillow lavas, lapilli and augite-rich tuff with interbeds of basaltic sandstone, siltstone, and conglomerate. Includes some basaltic andesite and, near the top of the sequence, some dacite. Potassium-argon ages on middle and lower parts of sequence range from about 43 to 46 Ma (Magill and others, 1981): one potassium-argon age from dacite near top of sequence is about 40 Ma (see Wells and others, 1983)

Tss **Undifferentiated sedimentary rocks (late Eocene)**—Thick- to thin-bedded marine tuffaceous mudstone, siltstone, and sandstone; fine to coarse grained. Contains calcareous concretions and, in places, is carbonaceous and micaceous. Includes the Nestucca Formation, which contains a foraminiferal assemblage assigned to the upper Narizian and lowermost Refugian Stages (Snavely and others, 1969)

Ty **Yamhill Formation (late middle Eocene)**—Massive to thin-bedded concretionary marine siltstone and thin interbeds of arkosic, glauconitic, and basaltic sandstone; locally contains interlayered lapilli tuff. Foraminiferal assemblages in siltstone referred to the upper Ulatisian and lower Narizian Stages (Snavely and others, 1969); assigned to late middle Eocene coccolith Zone CP14a (Bukry and Snavely, 1988)

Tt **Tyee Formation (early middle Eocene)**—Micaceous, carbonaceous turbidite sandstone and siltstone intruded by basalt sills. Very thick sequence of rhythmically bedded, medium- to fine-grained micaceous, feldspathic, lithic, or arkosic marine sandstone and micaceous carbonaceous siltstone; contains minor interbeds of dacite tuff in upper part. Foraminiferal assemblages are referred to the Ulatisian Stage (Snavely and other, 1964); assigned to early middle Eocene coccolith Zones CP12a, b (Bukry and Snavely, 1988). Groove and flute casts indicate deposition by north-flowing turbidity currents (Snavely and others, 1964)

Tsr **Siletz River Volcanics (lower Eocene)**—Pillow basalt and breccia with filled lava tubes, includes lower Eocene Salmon River Formation south of latitude 45°10'. Aphanitic to porphyritic, vesicular pillow flows, tuff-breccias, massive lava flows and sills of tholeiitic and alkalic basalt. Upper part of sequence contains interbeds of basaltic siltstone and sandstone, basaltic tuff, and locally derived basalt conglomerate. Rocks of unit pervasively zeolitized and veined with calcite. Most of these rocks are of marine origin and have been interpreted as oceanic crust and seamounts (Snavely and others, 1968). Foraminiferal assemblages referred to the Ulatisian and Penutian Stages (Snavely and others, 1969); coccolith flora assigned to Paleocene and lower Eocene Zones CP9 to CP10 (Bukry and Snavely, 1988); K-Ar ages range from 50.7±3.1 to 58.1±1.5 Ma (Duncan, 1982)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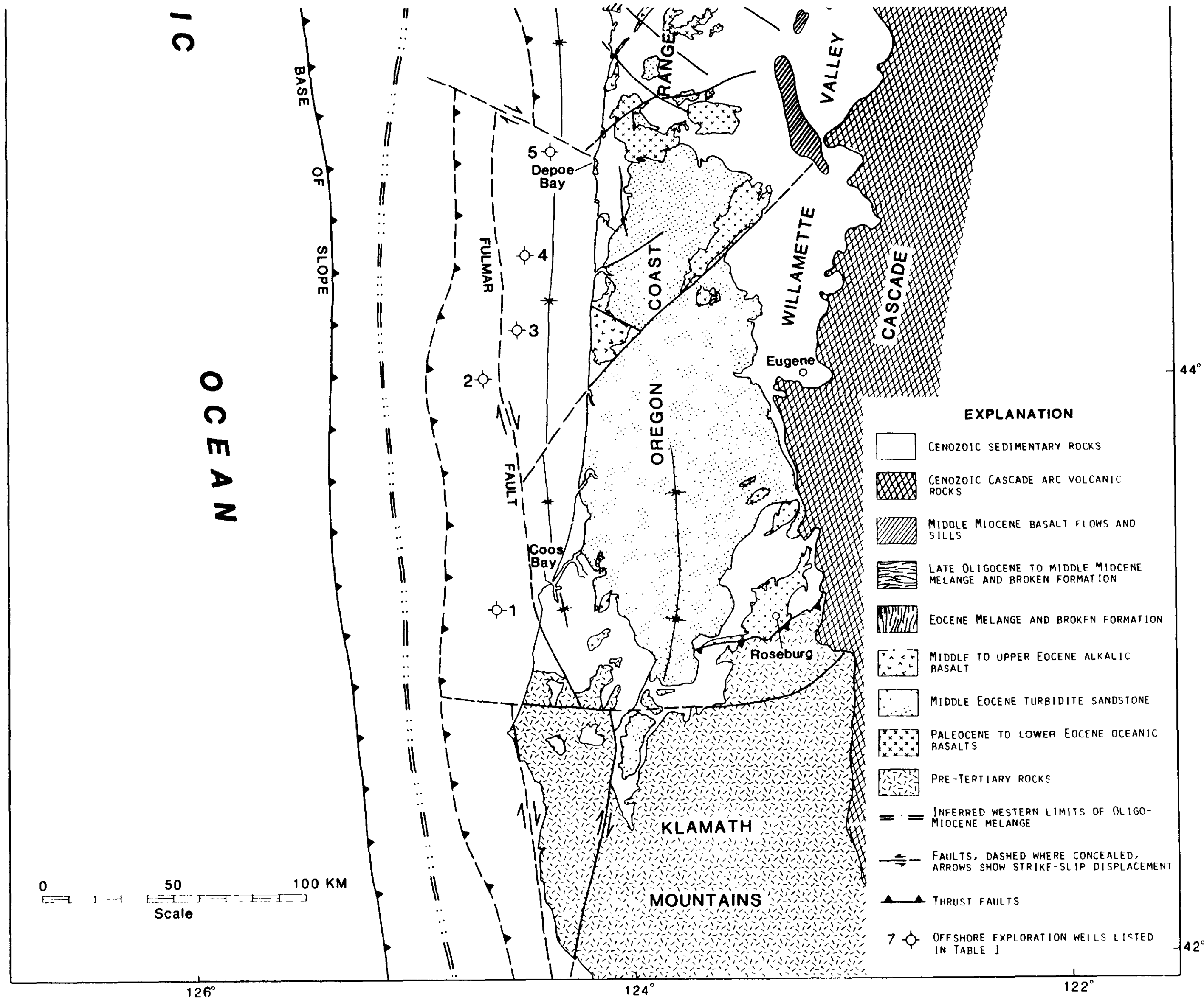

Figure 2. Generalized onshore geologic map of western Oregon and Washington, and southern Vancouver Island, B.C., with inferred locations of major faults on the continental shelf. Offshore faults concealed by younger strata are indicated by short dashed lines. LRF, Leech River fault; SJF, San Juan fault. Outcrops of middle Miocene basalt not shown in Willamette Valley; upper middle Eocene volcanics not shown in the eastern part of Puget Sound.

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 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. 2; 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). The most popular model for the origin of these basalts is tectonic accretion of oceanic islands (for example, Duncan, 1982; Wells and others, 1984). However, we prefer a 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. 3; 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. 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.

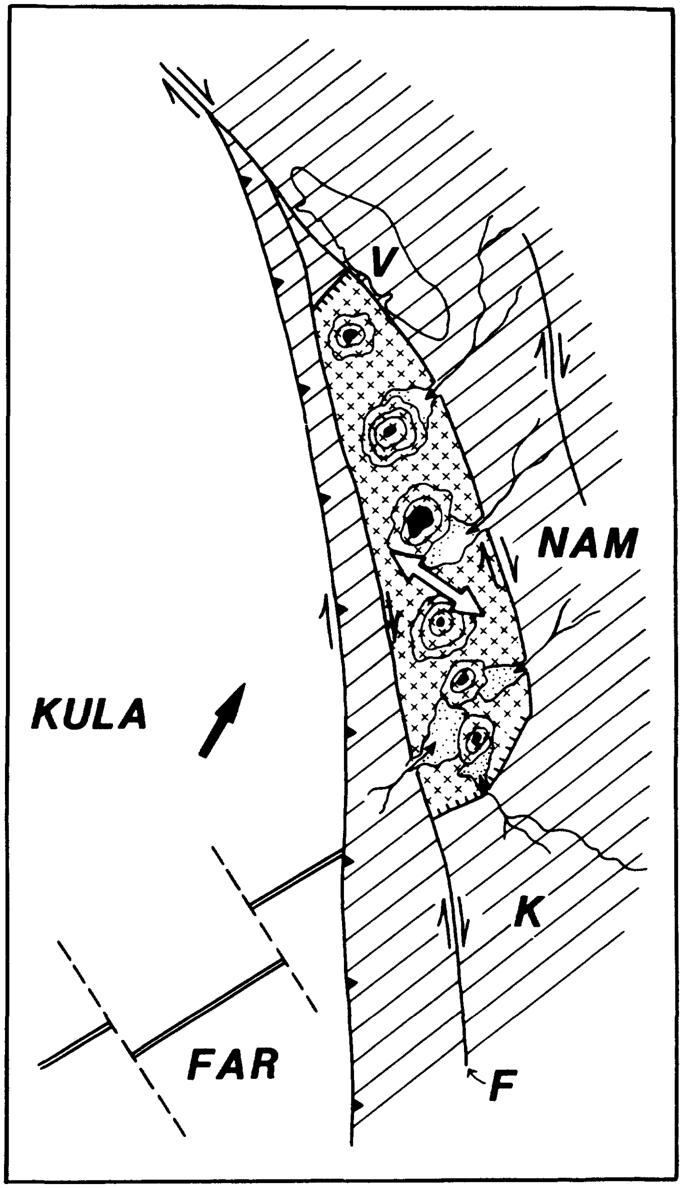

Figure 3. Diagram showing inferred continental-margin-rifting model for the origin of the Paleocene and lower Eocene oceanic basalt (x pattern) and oceanic islands (circular areas) in western Oregon and Washington. K, Klamath Mountains; V, Vancouver Island, B.C.; FAR, Farallon plate; KULA, Kula plate; NAM, North American plate; F, Fulmar fault. Arrows denote direction of movement of the Kula plate relative to the North American plate. Open double-pointed arrow represents inferred regional extension (Engebretson and others, 1985).

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 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).

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 (fig. 2). 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 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 (fig. 2, see also Wells and others, 1983).

In the 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 by convergence 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 (MacLeod and others, 1977; Snavely and others, 1986). This resulted from northward movement of the Paleogene Olympic-Coast Range 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).

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.

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 is interpreted as 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. Elsewhere, 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. 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).

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).

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 late 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.

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. 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 (see Snavely and Wagner, 1982).

Off northwest Washington and southern Vancouver Island, late Miocene strata rest unconformably on older Tertiary rocks (Shouldice, 1971; Snavely and Wagner, 1980). Although most strata of this age are restricted to the shelf, late 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, 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 (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. 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).

DEFORMATION

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 echelon 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).

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.

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.

NORTHWEST PETROLEUM ASSOCIATION 9TH ANNUAL FIELD TRIP
CENOZOIC GEOLOGY OF COASTAL NORTHWEST OREGON

Road Log [1]

Field trip stops are shown by numbered filled circles on a geologic sketch map of the northern Oregon Coast Range (fig. 1). A generalized stratigraphic section for rocks exposed in the Hebo area is shown in figure 4 and for rocks exposed in the Tillamook in figure 5. The time stratigraphic correlation of coccolith zones and foraminiferal stages are shown in figure 6.

Mileage

00.0 Start Field Trip at Shilo Inn, Lincoln City, Oregon. Head east out of the parking lot toward U.S. 101

00.3 Intersection of U.S. 101 - turn left and proceed northeastward on U.S. 101

00.5 Roadcut on left is west-dipping thin-bedded tuffaceous siltstone and sandstone of the late Eocene Nestucca Formation capped with Pleistocene marine terrace deposits

00.8 Devils Lake to the right - a marine transgression occurred in the lake about 5,000 B.P.; Devils Lake Golf Course on the left

1.8 Concealed contact of the late Eocene Nestucca Formation (CP15a) and the late middle Eocene Yamhill Formation (CP14a)

2.6 Junction of 101 and State Highway 18. Turn right toward Portland on Highway 18 and follow the road along the valley of the Salmon River

4.1 Otis Junction

4.4 Contact of the Yamhill Formation and the Beds of Otis Junction, an early middle Eocene equivalent of the Tyee Formation (CP12b). The Otis beds crop out only on the west side of the Siletz River volcanic high (see discussion at STOP 3)

4.7 Concealed contact between Beds of Otis Junction and the sedimentary volcanic rocks of the Salmon River Formation of early Eocene age (Snavely, 1991). The rocks of the Salmon River Formation are complexly folded and faulted and are well exposed along the Salmon River

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[1] The authors wish to express their appreciation to Dr. Alan Niem, Oregon State University, who assisted in leading this field trip.

Figure 4. GENERALIZED STRATIGRAPHIC SECTION
HEBO AREA
NW OREGON COAST RANGE
(no vertical scale indicated)

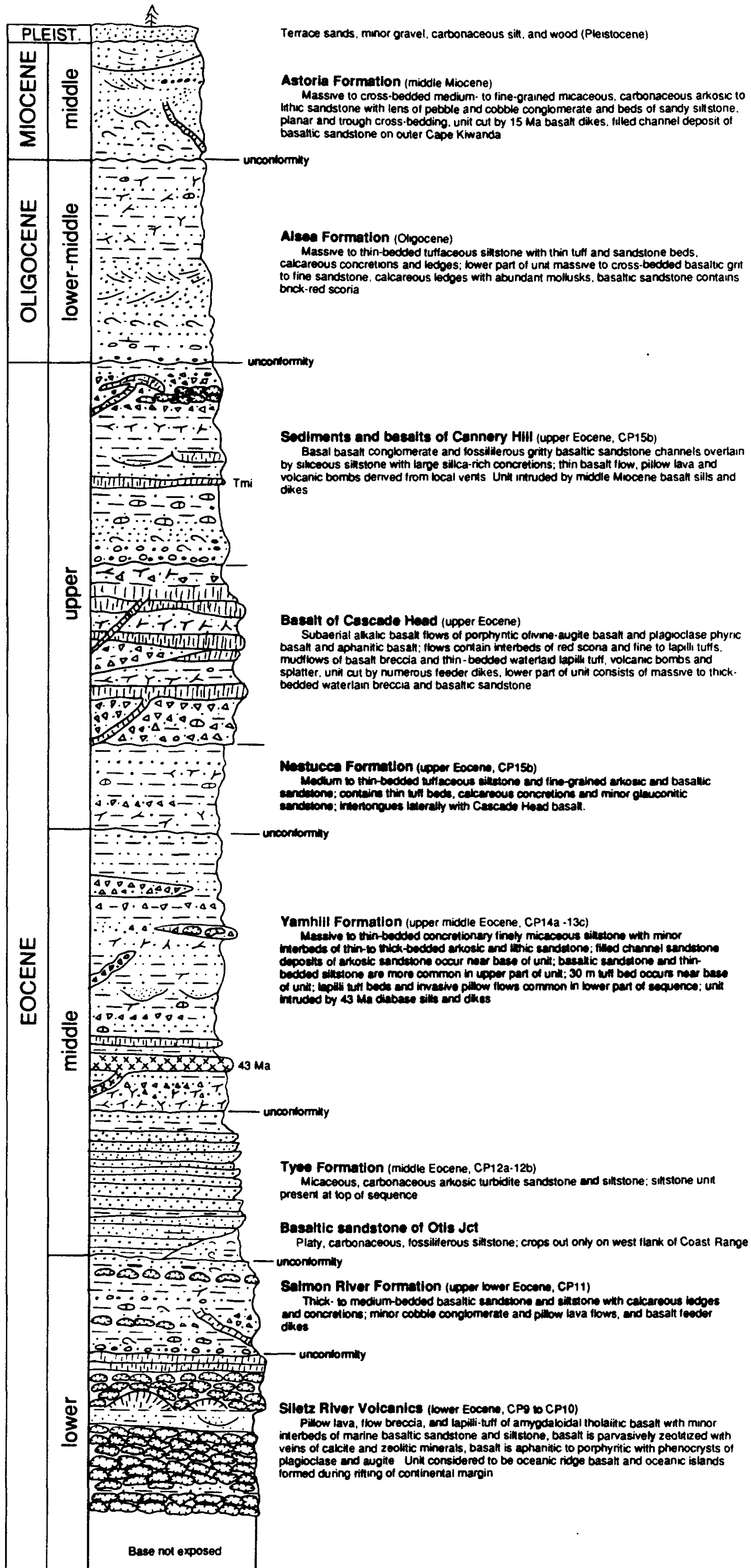


Figure 5. GENERALIZED STRATIGRAPHIC SECTION TILLAMOOK AREA NW OREGON COAST RANGE

(no vertical scale indicated)

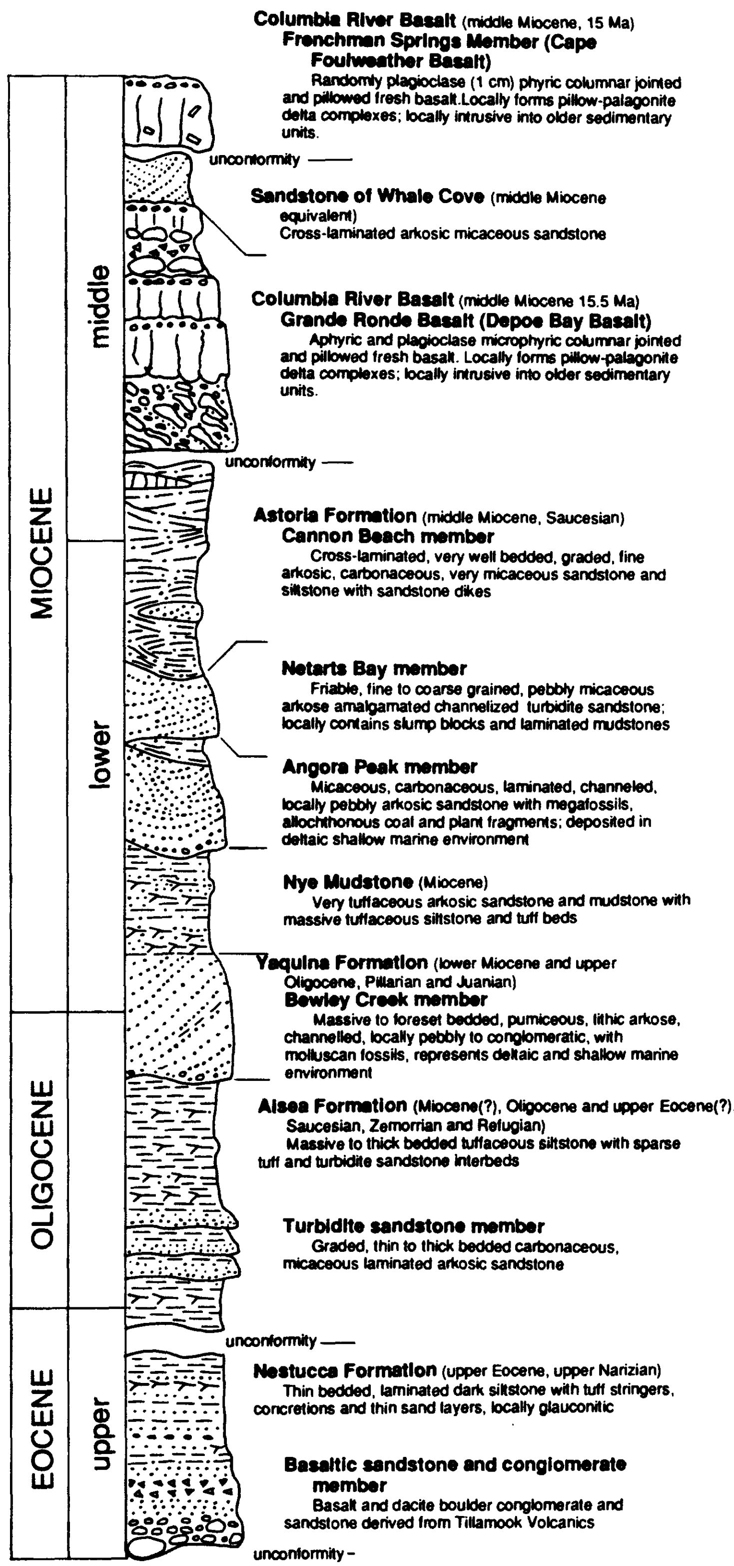
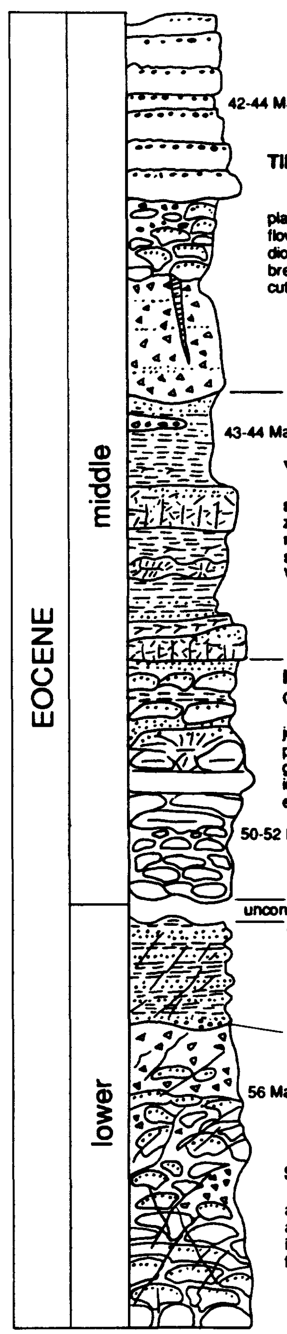


Figure 5. GENERALIZED STRATIGRAPHIC SECTION
TILLAMOOK AREA
NW OREGON COAST RANGE--Continued



Tillamook Volcanics (upper middle Eocene, Narizian, CP14a, ~43 Ma)
Upper part is several kilometers of aphyric to very plagioclase-pyroxene phyric basalt and basaltic andesite flows; dacite is locally abundant at top; upper unit intruded by diorite; lower unit is mostly basalt lapilli breccia and pillow breccia overlain by pillow basalt; abundant Tillamook dikes cut this and all older units

Yamhill Formation (upper middle Eocene, CP14a - 13c)
Laminated well-bedded to locally massive tuffaceous siltstone with tuff stringers; moderately well indurated cut by zeolitic diabase sills which locally make up the predominate rock type; also includes locally micaceous and basaltic sandstone and siltstone and oil shale beneath Tillamook Volcanics; beds at base of unit are very tuffaceous

Hembre Ridge Volcanics (lower middle Eocene, CP12a or b)
Mostly aphyric to slightly plagioclase phyric columnar jointed and pillow basalt, with interbedded sedimentary rocks; pillow basalt is somewhat altered, with pyrite and zeolite and greasy clay on fracture surfaces; sedimentary interbeds include tuff siltstone and very micaceous sandstone, probably equivalent to the Tyee Formation

Trask River Beds (lower Eocene, CP11)
Thin bedded, graded fine basaltic sandstone and siltstone, locally tectonized with calcite veins and abundant shear zones; dip is steep (~50°) along Trask River; locally conformable on or interfingers with underlying Siletz River Volcanics

Siletz River Volcanics (lower Eocene, CP9 to CP11)
Upper part is basalt lapilli breccia, basalt pillow breccia and basaltic sandstone; lower part is pillowed to massive aphyric basalt, upper flows are very plagioclase phyric; basalt is tectonized with zeolite, calcite and clay vein and vesicle fillings; matrix is generally greenish and altered

Epochs		Coccolith Zones[1]		Foraminiferal Stages[2]
Oligo			U	Refugian
Eocene	late	CP16a	L	
		CP15b	U	Narizian
		CP15b	L	
	middle	CP14a CP13c	U	Ulatisian
		CP12b CP12a	L	
	early	CP11 CP10 CP9		Penutian

[1]Bukry, 1973; Okada and Bukry, 1980
[2]Rau,1981

Figure 6. Correlation of Coccolith Zones and Foraminiferal Stages

6.7 Rose Lodge #1

As we proceed eastward we are going downsection. The high hills at 12 o'clock are held up by late middle Eocene diabase sills up to 1000 feet thick

7.6 Road junction to Cougar Mountain, which is a stock of camptonite

8.0 Rose Lodge #2

8.3 The conglomerate to the right is at the base of the Salmon River Formation. The boulder and cobble conglomerate consists of basalts and diabase derived from the underlying Siletz River Volcanics

8.9 Contact between the lower Eocene Salmon River Formation (CP11) and the Eocene Siletz River Volcanics (CP10)

9.0 Widow Creek Quarry, - the type section of the Siletz River Volcanics (Snavely and Baldwin, 1948) with excellent exposures of pillow lavas

9.1 Turn right on Widow Creek road. Proceed across the Salmon River and turn right into Kaufman Quarry

9.2 **STOP #1 — Kaufman Quarry,** Lower Eocene Siletz River Volcanics (SRV)

Tholeiitic oceanic basalt of the SRV ranges in age from late Paleocene to early Eocene (Bukry and Snavely, 1988) and forms the basement of the Oregon Coast Range. Compositions are similar to ocean floor basalt with low K_2O and TiO_2 (Snavely and others, 1968) and have similar rare earth element (REE) patterns. At Ball Mountain, 7 miles to the southwest, pillow lava of alkalic basalt is overlain by subaerial flows of feldsparphyric basalt that formed an oceanic island.

Here, at the Widow Creek Quarry, close-packed amygdaloidal pillow lavas are in the upper part of the Siletz River Volcanics, and are interbeded with basaltic sandstone and siltstone containing a shallow-water coccolith of the lower Eocene Tribrachiatus orthostylus Zone (CP10). The upper part of the Siletz River Volcanics commonly contains thick units of lapilli tuff, tuff breccia, pillow lava, filled lava tubes, and basaltic siltstone, sandstone, and conglomerate. In the upper level of the quarry a 6-foot-thick basaltic sandstone with scattered basalt clasts forms a broad channel in the pillow lava. The lower level quarry contains a columnar-jointed filled lava tube overlain by a carapace of pillow lava. A N25°W fault with horizontal slickensides cuts the filled tube; such faults are commonly dextral where offsets can be determined.

Seven samples of Siletz River basalt collected in the Euchre Mountain Quadrangle 6-12 miles south of this stop have whole rock K/Ar dates that range from 52.9 to 58.1 Ma (Duncan, 1982). Pillow basalt in the lower Eocene Crescent Formation of southwest Washington and on the Olympic Peninsula are correlative.

9.3 Return to Widow Creek road, cross river to State 18, - turn left (large pillows are exposed in river bed)

Proceed west on State 18

10.5 Cross Slick Rock Creek, turn right, proceed west on North Bank Road

10.7 **STOP #2 — <u>Type section of the lower Eocene Salmon River Formation</u>**

Broad apron of lower Eocene basaltic sandstone and siltstone with minor interbeds of conglomerate and basalt flows and breccia were deposited adjacent to Siletz River oceanic islands. Here at the type section of the Salmon River Formation (Snavely, 1991), the strata contain calcareous ledges and concretions and zones of poorly preserved mollusks. Looking south from the bridge across the Salmon River, several irregular basalt dikes trending N40°W can be seen cutting the medium-bedded basaltic sandstone and siltstone.

The Salmon River Formation contains typical lower Eocene coccoliths of the <u>Discoaster</u> <u>lodoensis</u> Zone (CP11) which are found throughout much of the Oregon Coast Range, extending from near Roseburg (Umpqua Formation) to the Tillamook Highlands (beds of Trask River), a distance of about 150 miles. Correlative strata in northern Washington include deep marine siltstone and pillow basalt in the upper part of the Crescent Formation on the Olympic Peninsula.

Proceed west on North Bank Road. The roadcuts along this road are weathered basaltic sediments of the Salmon River Formation

14.0 **STOP #3 — <u>Oregon State Salmon River Fish Hatchery</u>**

Looking north across the Salmon River, the large road cut along State Route 18 consists of a sequence of fossiliferous medium- to thin-bedded finely micaceous, carbonaceous well-indurated lithic and basaltic sandstone and siltstone that is informally referred to as the Basaltic sandstone and siltstone of Otis. These strata unconformably overlie the Salmon River Formation and contain coccoliths assigned to lower middle Eocene <u>Rhabdosphaera</u> <u>inflata</u> Subzone (CP12b). East of the oceanic island formed by the Siletz River Volcanics, equivalent strata are the arkosic turbidite sandstones of the Tyee Formation. Deposition of the Tyee sandstone was restricted to the east side of the oceanic ridge and is correlative with the basaltic strata deposited west of the island as here near Otis. This interpretation is supported by geologic mapping north of the Salmon River as the Tyee Formation only crops out east of exposures of the Siletz River Volcanics along the Little Nestucca and Nestucca Rivers.

Return to North Bank Road, turn left and proceed west

14.6 The Otis strata are unconformably overlapped by the late middle Eocene (CP14a) Yamhill Formation.

14.7 Old U.S. 101 and North Bank Road junction

Turn right and proceed north on old 101

15.0 Turn left on East Three Rocks Road

Roadcuts are in weathered siltstone of the late middle Eocene Yamhill Formation

15.6 Junction U.S. 101

Turn right on 101, proceed north

16.4 Approximate concealed contact between the Yamhill Formation and the overlying late Eocene Nestucca Formation

16.6 Roadcut to left of thin-bedded tuffaceous siltstone and arkosic sandstone of the late Eocene Nestucca Formation

Road proceeds upsection to the overlying late Eocene Cascade Head Basalts

18.2 **Cascade Head** (no stop due to traffic hazards)

Road cut in late Eocene Nestucca Formation near the base of the Cascade Head Basalt. Here several feeder dikes to the overlying basalt flows and breccias of the Cascade Head Basalt cut the Nestucca Formation. The thin-bedded tuffaceous siltstone, with interbedded fine-grained arkosic and basaltic sandstone, contain a late Eocene coccolith flora (CP15a). The Nestucca Formation intertongues with chiefly subaerial alkalic basalt flows and breccia that formed oceanic islands in the forearc basin as here at Cascade Head and 60 miles to the south at Cape Perpetua-the type locality of the Yachats Basalt.

The Nestucca Formation is underlain by the middle Eocene Yamhill Formation which is exposed along Neskowin Creek just north of Cascade Head summit and is less than 200 feet stratigraphically below the summit

18.5 Contact between Nestucca Formation and overlying late Eocene basalts of Cascade Head

300 feet of tuff breccia and lapilli tuff in lower part of Cascade Head Basalt, which consist chiefly of subaerial flows with minor breccia and tuff interbeds

The geology on 101 between the summit and Neskowin is predominantly a sequence of northwest-dipping alkalic basalt flows, averaging about 20 feet thick, with tuff breccia interbeds. Cascade Head Basalts are about 1800 feet thick, and are underlain by late Narizian fossiliferous siltstone. A CP15a coccolith zone was assigned to this rock by Dave Bukry (Bukry and Snavely, 1988)

19.7 Large roadcut to left is west-dipping, thick-bedded to massive tuff breccia and lapilli tuff. The light colored clasts are concretions from the underlying Nestucca Formation.

19.8 Contact with overlying subaerial flows

North of the highway and Neskowin Creek, hornblende andesite dikes dated at 34 Ma cut the volcanic sequence

20.7 Flows of Cascade Head basalts on the north side of the road

21.7 The small coastal village of Neskowin (Snavely's first field headquarters in the Pacific Northwest, 1946)

North of Neskowin the road parallels the upper contact of the Cascade Head Basalts, marked by boulder conglomerate and basaltic sandstone

22.6 Concealed contact of Cascade Head Basalts and overlying late Eocene sedimentary rocks and basalt of Cannery Hill (Snavely and others, 1990)

23.7 Siltstone member of Cannery Hill unit on right is cut by 6-foot basalt dike of middle Miocene Depoe Bay Basalt-type. The light-colored concretions in the siltstone measure up to 3 feet in diameter and are very siliceous, about 60% SiO_2

23.8 Turn left (west) on Sahhali Drive and proceed uphill. The road is in dark-gray siliceous mudstone of the Sedimentary rocks and basalt of Cannery Hill (upper Eocene)

24.0 Base of basalt flow (titanium rich) of Cannery Hill sequence which is overlain by basalt cobble and boulder conglomerate and basaltic sandstone of latest Eocene age

24.1 **STOP #4 —**

Basaltic sandstone and basalt of late Eocene Cannery Hill sequence. The basalt of Cannery Hill is part of a late middle to late Eocene episode of coastal basalt volcanism that includes the basalt of Cascade Head, Yachats Basalt and Tillamook Volcanics. These high TiO_2 basalts were erupted from regional WNW-trending dike swarms and represent continued rifting of the continental margin in the Eocene.

These wavy, irregular and thin-bedded basaltic sandstones may represent (1), base-surge deposits from a group of small eruptive centers located near the coast; or (2), slumping of basaltic sandstone strata on steep flank of a vent? These thin-bedded sandstone beds are overlain by massive to thick and cross-bedded basaltic sandstone of the overlying Oligocene Alsea Formation

Beautiful view of the Oregon Coast at this stop, from Cascade Head to the south, to Cape Kiwanda and Cape Lookout to the north

24.6 Return to U.S. 101

25.1 The hills to the east are held up by Cascade Head Basalt

25.3 Roadcut is filled channel of massive basaltic sandstone

25.9 Viewpoint to the left (no stop)

Roadcut to the east is lower Oligocene basaltic sandstone of the Alsea Formation overlain by a 150-foot-thick middle Miocene basalt sill

27.3 Oretown

28.2 Cross the Little Nestucca River

29.6. Junction of U.S. 101 and the highway to Pacific City (home of the Dory Fleet). The roadcut at the intersection is weathered Yamhill Formation siltstones and sandstones

The roadcuts along this road are mainly in the Nestucca Formation and the Sedimentary rocks and basalts of Cannery Hill. Poor exposures of tuffaceous sediments with interbedded basalt flows and breccia intruded by middle Miocene basalt dikes and sills

30.8 To the left is Nestucca Bay -- excellent Salmon fishing

31.4 Roadcut of massive basaltic sandstone of the Alsea Formation cut by Miocene basalt sills

32.3 City center of Pacific City, turn left towards the ocean

32.6 Cross the Nestucca River. Turn right (north) to Cape Kiwanda. The low wooded hill at 1 o'clock is formed by a large sand dune

33.5 **STOP #5 — Lunch Time at Cape Kiwanda**

Cape Kiwanda is formed by massive to medium-bedded micaceous arkosic sandstone of the middle Miocene Astoria Formation. Here, on the south side of the Cape, the Astoria Formation (Angora Peak member of Cooper, 1981) rests unconformably on siltstone of the lower Oligocene Alsea Formation (Snavely and others, 1990). The lower part of the Astoria sandstone is silty, carbonaceous, and bioturbated. In places, pholad burrows filled with Astoria sandstone extend 4 to 6 inches into the underlying Alsea siltstone.

The Astoria Formation exposed here is interpreted as a high-energy, wave-dominated delta that prograded onto a steep shelf (Snavely and others, 1977; Cooper, 1981). Part of the sand most likely was transported into the deep marginal offshore basin by turbidity currents or fan channels and formed potential reservoir rocks for petroleum. Six porosity and permeability determinations have been published for the Astoria Formation along the central Oregon Coast (Snavely and others, 1977) and show a range of porosity from 20.4 to 29.2 percent, and permeability from 3 to 1,682 millidarcys.

At the extreme west end of the Cape, a filled channel deposit of basaltic sandstone cuts the arkosic sandstone beds of the Astoria. The basalt sand is composed of grains derived from the underlying Cascade Head basalts. Several lenses of conglomerate are present in the Cape Kiwanda Astoria sandstones and contain clasts of basalt and metamorphic rocks. The Cape is capped by Pleistocene terrace deposits which in turn are overlain by late Pleistocene and Holocene dune sands.

A 3-foot basalt dike of Depoe Bay Basalt (15 Ma) cuts the sandstone sequence--this dike is probably related to the 500-foot-high basalt plug that forms Haystack Rock, 0.8 miles offshore.

Reset Milage

0.0 Leave parking lot and head north on Three Capes Road through stabilized coastal dune fields

1.3 Intersection of Thousand Trails and Woods Junction

Head straight north on Three Capes Road

1.7 Roadcut to the right is tuffaceous siltstones of the Oligocene Alsea Formation. The view to the north is Cape Lookout,- a middle Miocene sequence of Columbia River Basalt submarine and subaerial flows, which projects 2 miles west into the Pacific Ocean. The sheer south-facing cliff is approximately 500 feet high.

This cape may represent a west-trending valley filled with basalt flows which are erosionally resistant and form inverted topography

2.1 City limits of Tierra Del Mar

3.8 Sand Lake estuary on left

6.6 Sand Lake Store

7.6 Sand Lake junction - turn left (west) toward Cape Lookout State Park

8.4 The road crosses an active dune field that is a recreational area for off-road vehicles. Dunes are encroaching on the forest to the northeast

9.6 Weathered outcrop of lower Miocene Nye Mudstone

10.2 Road continues upsection into the Astoria Formation, with local basaltic grit and hummocky crossbedded arkosic sandstone

10.6 **STOP #6** — Viewpoint, stop is just below Astoria - middle Miocene basalt contact. Excellent vista to the south of Sand Lake, Cape Kiwanda, and Cascade Head on the horizon.

10.9 Parking lot at the top of Cape Lookout. Columnar jointed and crudely pillowed Grande Ronde Basalt of the Columbia River Group, correlative with Depoe Bay Basalt in the Newport area mapped by Snavely and others (1976a)

11.4 Pillowed Grande Ronde Basalt

12.5 **STOP #7** — Anderson Viewpoint. View of Netarts Spit, Three Arch Rocks, Cape Meares, Netarts Bay. Weathered basalt in the roadcut

13.6 Cape Lookout State Park entrance

14.2 Netarts Bay on the left. Road follows the east shore of the bay

16.4 Wee Willies

17.4 Three Capes junction

Take the left fork along Netarts Bay

18.8 Netarts Landing - bear right

18.9 Stop sign, turn left on Netarts Highway through Netarts

19.4 Turn left at Happy Camp RV park entrance

19.7 **STOP #8** — The mouth of Netarts Bay. Public parking on beach. To the south a view of west dip slope of Grande Ronde Basalt at Cape Lookout to the south

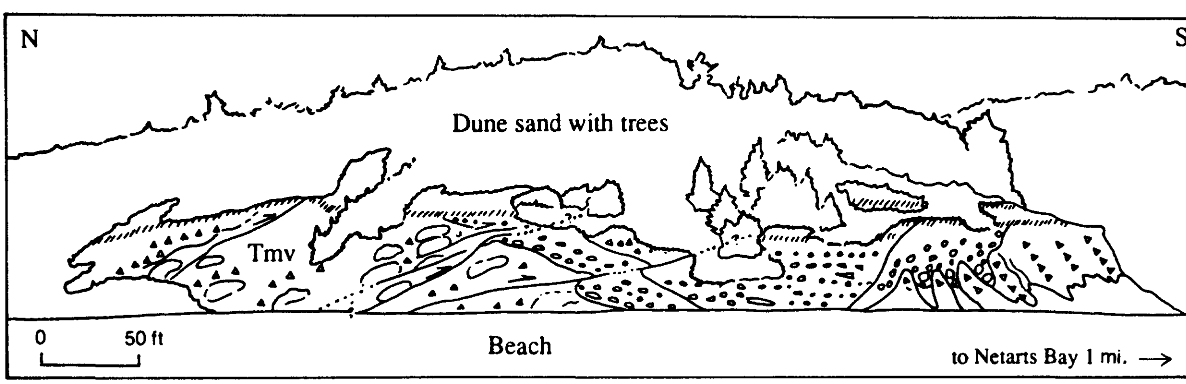


Figure 7.--Line drawing of 650-foot long and 65-foot-high seacliff exposure near Happy Camp, north of Netarts Bay, Oregon. Tmv is Miocene (15 Ma) Columbia River Basalt pillows and breccia (triangles). Thrust faults cut basalt and Pleistocene channel fills (gravel symbols) containing wood fragments. Hachured lines indicate buried soils (after Wells and others, 1992).

These faults may be related to a record of episodic, rapid Holocene subsidence of coastal estuaries in Oregon and Washington that has been interpreted to represent deformation during large subduction zone earthquakes along the convergent plate boundary (Atwater, 1987; Peterson and Darienzo, 1988). Our studies of the local geology and late Cenozoic deformation of several coastal embayments suggest that, in addition to the regional subsidence, local structural control may also be important. Tillamook Bay and Netarts Bay in northwest Oregon are bounded by WNW-trending high-angle reverse or thrust faults along their northern margins. In the seacliff at the north end of Netarts Bay, Grande Ronde Basalt (15 Ma) is thrust southward over late (?) Pleistocene channel deposits on 3 shallow, north-dipping faults with up to 30 feet of cumulative offset. A Pleistocene terrace at the top of the cliff varies in elevation from about 40 feet on the footwall block to about 65 feet on the hanging wall block and may reflect differential uplift. Similar north-dipping young faults are observed on N-S seismic reflection profiles about 6 miles offshore (figure 8), suggesting that the Netarts Bay faults are part of a substantial thrust system oblique to the margin. Quaternary subsidence of Netarts Bay may in part reflect accommodation of local and/or regional strain on these oblique boundary structures. The north-dipping thrusts indicate a component of N-S shortening in the Coast Range which is consistent with the pattern of late Cenozoic deformation and with the present-day crustal seismotectonic regime in the Puget-Willamette lowland.

20.0 Proceed north from Happy Camp. Roadcuts are stabilized dunes above the RV Park

21.8 View of the town of Oceanside, Three Arch Rocks, and Maxwell Point. All are composed of Miocene Grande Ronde Basalt of the Columbia River Basalt Group. NOTE: North-trending normal fault on the west side of the landslide scar in Maxwell Point. Top of scarp is less than 20 feet from House on the Hill Motel (soon to be Four Arch Rocks).

22.0 Take the right fork and follow Three Capes scenic route

22.8 View of the south face of Cape Meares showing seaward-dipping pillow flows. Roadcuts on the right are weathered pillow basalt

23.5 Quarry in columnar jointed flow of Grande Ronde Basalt

24.4 Turn left at entrance to Cape Meares State Park

24.7 WWII concrete pillbox on right

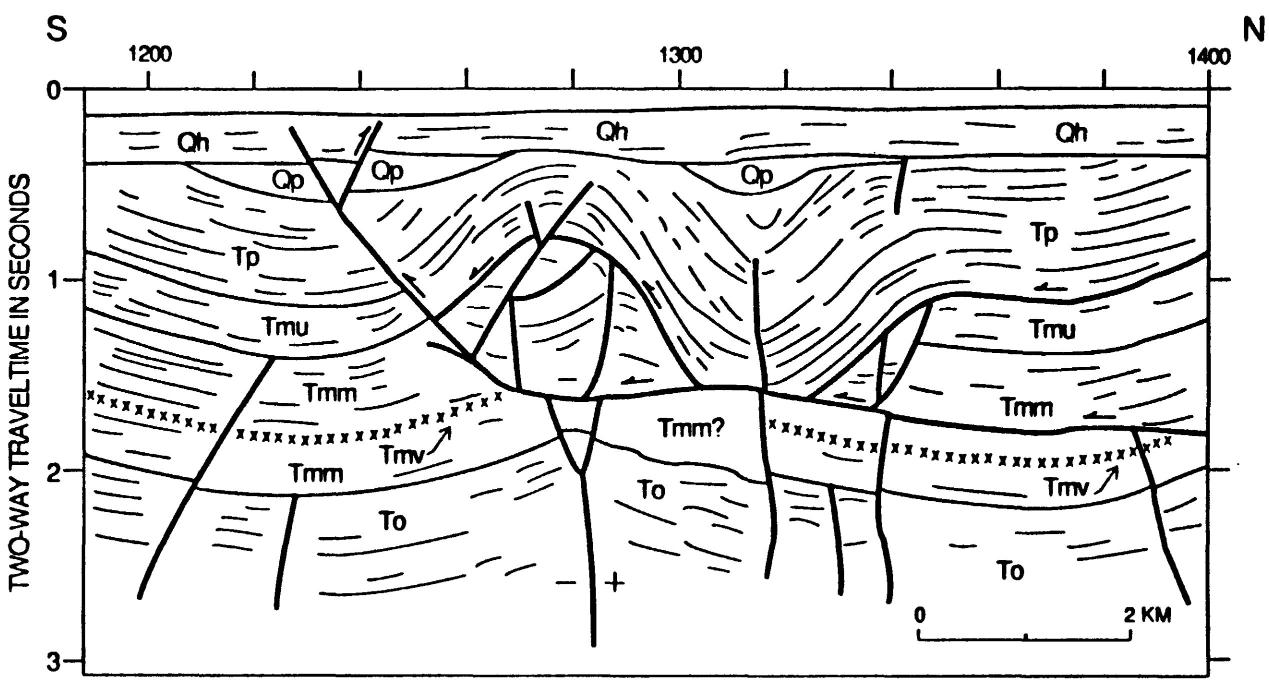


Figure 8. Geologic interpretation of a segment of USGS multichannel seismic-reflection profile 76-6 off Netarts Bay, Oregon. Symbols: Qh, Holocene; Qp, Pleistocene; Tp, Pliocene; Tmu, upper Miocene; Tmm, middle Miocene; To, Oligocene; small x's with symbol Tmv, middle Miocene (15 Ma) basalt flow; faults, half arrows indicate direction of movement on thrust faults.

24.9 **STOP #9 —** Cape Meares State Park parking lot

On the trail towards the lighthouse, stop at the second viewpoint on the right for a spectacular view of middle Miocene basalt flows and breccia (figure 9).

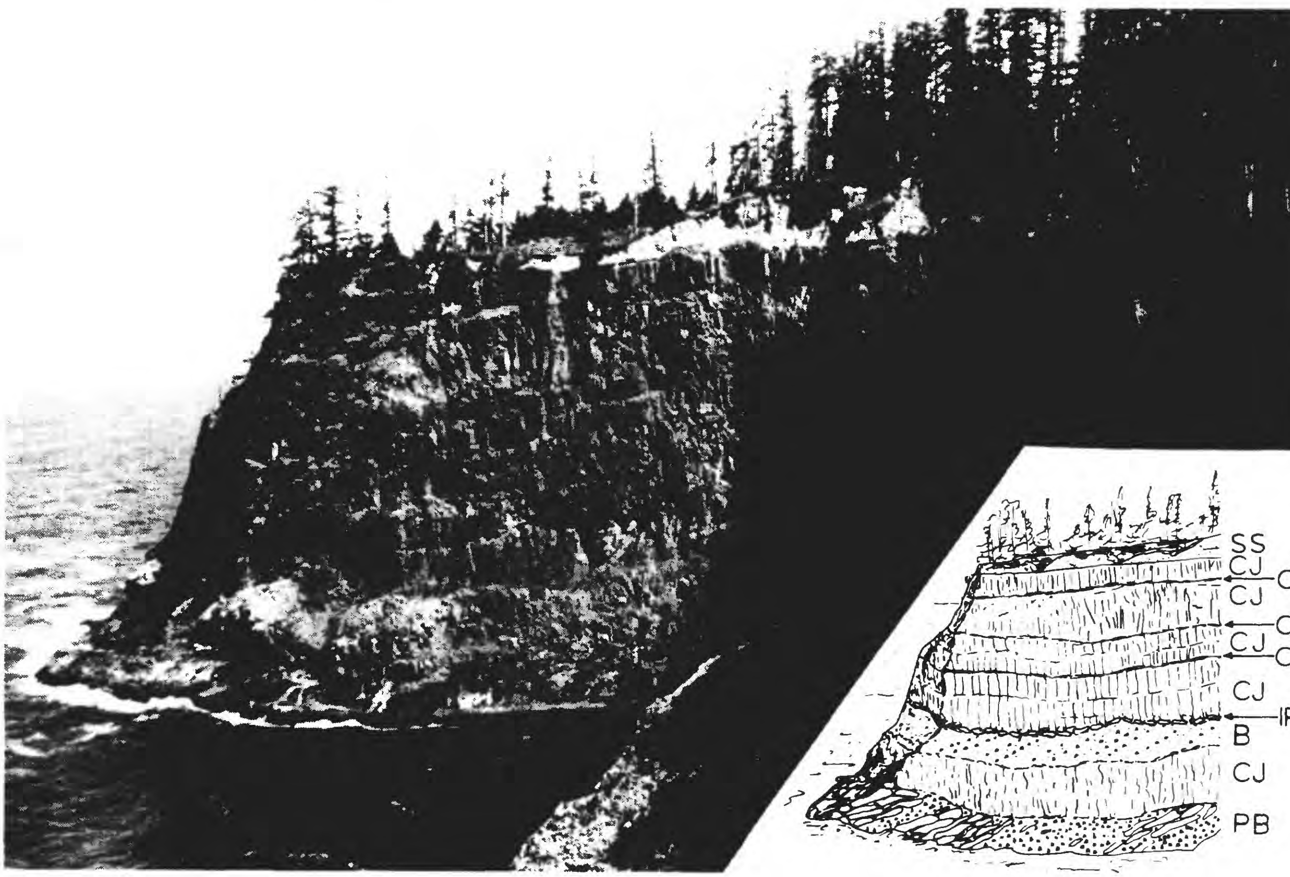


Figure 9.--Grande Ronde Basalt (Depoe Bay Basalt of Snavely and others, 1973) exposed 650 feet north of lighthouse at Cape Meares. Foreset-bedded breccia and pillows (PB) at the base are overlain by a rudely columnar-jointed flow (CJ) which is in turn overlain by foreset-bedded breccia (B). The upper four columnar-jointed flows are separated by oxidized zones (O) and were formed subaerially; the lowest of these flows has incipient pillows (IP) developed at its base. Basalt flows are overlain by thick-bedded Miocene sandstone equivalent to sandstone of Whale Cove at Depoe Bay (SS).

Return to Three Capes Road

25.5 Junction with Three Capes Road, turn left

25.9 View to the left from the top of Cape Meares, an active landslide. At 12 o'clock a view of Tillamook Bay and the late middle Eocene Tillamook Volcanics, sandstone at Garibaldi, Neahkanie Mountain Miocene sill of Grande Ronde Basalt is at the skyline

NOTE: Road damage from active slide, slidetoe is cut away by wave erosion at Cape Meares Beach. Major change in geometry of spit in this century. Old town of Bay Ocean

27.4 Turn right towards Tillamook at T junction

27.7 Bay Ocean spit road. A view of Tillamook Highlands and the bay. The road follows the bay and the cliffs along the road are deltaic shallow marine beds of the Astoria Formation.

No safe pull out

Skyline on left is the Tillamook Volcanics

32.8 Junction with the Tillamook-Netarts Road

Turn left toward Tillamook

32.9 Bridge across the Tillamook River. The alluvial flats are prime dairy country and is the home of the Tillamook Cheese Factory and other cheese factories

34.4 Junction of U.S. 101 in downtown Tillamook

Turn right (south) on U.S. 101

37.9 WWII Blimp Hangers, one was destroyed by fire in August 1992

39.6 Rest area

39.9 In Tillamook River are good exposures of turbidite sandstone of the lower part of the Oligocene Alsea Formation; contains foraminifers referrable to the Zemorrian Stage

END TRIP

REFERENCES

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, 1973, Low-latitude coccolith biostratigraphic zonation, chap.16, *in* Edgar, N.T., Saunders, J.B. and others, Initial Reports of the Deep Sea Drilling Project, v. 15: Washington, U.S. Government Printing Office, p. 785-703.

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., 1992, 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.

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.

Grant, W.C. and Minor, R., 1991, Paleoseismic evidence and prehistoric occupation associated with the late Holocene submergence, Northern Oregon Coast: EOS, Transactions, *American Geophysical Union*, v. 72, p. 313.

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.

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.

Okada, Hisatake, and Bukry, David, 1980, Supplementary modification and introduction of code numbers to the low-latitude coccolith biostatigraphic zonation (Bukry, 1973, 1975): Marine Micropaleontology, v. p. 321-325.

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.

Simpson, R. W., and Cox, A. V., 1977, Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range: Geology, v. 5, p. 585-589.

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., and Baldwin, E.M., 1948, Siletz River Volcanic Series, northwestern Oregon: American Association of Petroleum Geologists Bulletin, v. 39, no. 6, p. 806-812.

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.

Walker, G.W. and MacLeod, N.S., 1991, Geologic Map of Oregon: U. S. Geological Survey Map, 2 sheets, scale 1:500,000.

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.

Wells, Ray E., Snavely, Parke D., Jr., and Niem, Alan R., 1992, Quaternary thrust faulting at Netarts Bay, northern Oregon coast: Geological Society of America, Abstracts with Programs, v. 24, no. 5, p. 89.

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.