Chapter 2

Total Petroleum Systems and Geologic Assessment of Undiscovered Hydrocarbon Resources of the Western Oregon and Washington Province

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By Michael E. Brownfield

Chapter 2 of 4

Geologic Assessment of Undiscovered Hydrocarbon Resources of the Western Oregon and Washington Province

By U.S. Geological Survey Western Oregon and Washington Province Assessment Team

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Total Petroleum Systems and Geologic Assessment of Undiscovered Hydrocarbon Resources of the Western Oregon and Washington Province

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Abstract

The U.S. Geological Survey (USGS) recently completed an assessment of the undiscovered oil and gas resources of the Western Oregon and Washington Province, which includes about 40,000 mi^2 in western Oregon and Washington. The assessment was geology based using the total petroleum system (TPS) concept. The primary geologic elements of a TPS include hydrocarbon source rocks (source rock maturation and hydrocarbon generation and migration), reservoir rocks (quality and distribution), and traps for hydrocarbon accumulation. Using these criteria, the USGS assessment team defined three TPSs, each with one assessment unit (AU): (1) the Cretaceous-Tertiary TPS and the Western Oregon and Washington Conventional Gas AU, (2) the Tertiary Marine TPS and the Tertiary Marine Gas AU, and (3) the Tertiary Coalbed Gas TPS and the Eocene Coalbed Gas AU.

More than 23,000 ft of Paleogene volcanic rocks, marine mudstone and sandstone, and nonmarine arkosic sandstone, mudstone, carbonaceous shale, and coal are present in western Oregon and Washington. These rocks include potential mature petroleum source rocks and reservoir rocks.

The USGS assessed both undiscovered conventional oil and gas and undiscovered continuous (unconventional) gas in the Western Oregon and Washington Province, resulting in estimated mean volumes of 2,214 billion cubic feet (BCF) of undiscovered natural gas and 15 million barrels of oil (MMBO). Sixty-seven percent (1,489 BCF) of the undiscovered gas is contained within the hypothetical Eocene Coalbed Gas AU in western Oregon and Washington. The mean estimated volume of gas for the Western Oregon and Washington Conventional Gas AU is 454 billion cubic feet of gas (BCFG), with an estimated mean size of the largest reported gas field of 85 BCFG. For the Tertiary Marine AU, the estimated mean volume is 249 BCFG, with the estimated mean size of the largest expected gas field of 101 BCFG. The assessed mean undiscovered volume of oil in the Tertiary Marine Gas AU is 15 million barrels of oil (MMBO), with estimated means of 22 BCFG for associated gas and 1 million barrels of natural gas liquids. The mean size of the largest expected oil field is 9 MMBO.

Introduction

As part of the U.S. Geological Survey's (USGS) effort to assess the potential for undiscovered petroleum accumulations, the USGS recently conducted an assessment of the undiscovered oil and gas resources of the Western Oregon and Washington Province (fig. 1). This report supplements the 2009 assessment (Brownfield and others, 2009) of the province by providing additional geologic detail concerning the defined total petroleum systems (TPS) and assessment units (AU), as well as a more detailed rationale for the quantitative assessment input.

The Western Oregon and Washington Province includes all of Oregon and Washington north of the Klamath Mountains and west of the approximate crest of the Cascade Range. The province extends offshore to the 3-mi limit of State waters on the west and to the U.S.-Canada International Boundary in the Strait of Juan de Fuca and Canada on the north. The province measures about 450 mi in a north–south direction and 50–160 mi east–west, encompassing approximately 40,000 mi^2 (fig. 1).

Before 1979, the only oil and gas production in the province was in Washington. In Watcom County, near Bellingham, Wash., small amounts of gas were produced from the Paleogene Chuckanut Formation below Quaternary gravels, and about 12,000 barrels of oil and associated gas were produced west of Aberdeen, Wash., from 1957 to 1961. Currently, the only hydrocarbon production is gas from the Mist field in northwestern Oregon (fig. 1) that was discovered in May 1979. The Mist field has produced about 65 billion cubic feet of gas (BCFG) through 2008 (Oregon Department of Geology and Mineral Industries, 2009).

In 1995, eight conventional plays were assessed in Province 4 by the USGS (Johnson and Tennyson, 1995): Bellingham Basin Gas Play (0401), Southeastern Puget Lowland Gas Play (0402), Puget Lowland Deep Gas Play (0403), Tofino-Fuca Basin Gas Play (0404), Western Washington Melange Play (0405), Southwest Washington Miocene Sandstone Play (0406), Cowlitz-Spencer Gas Play (0407), and Southwestern Oregon Eocene Gas Play (0410). Another conventional play, the Astoria Play (0408), was not formally assessed because

Figure 1. Western Oregon and Washington Province located in western Oregon and Washington; boundary is shown in red. Cretaceous-Tertiary Composite Total Petroleum System (TPS) is shown in orange. Eocene Coalbed Gas TPS is shown in dark blue. Tertiary-Marine TPS is shown in dark green. Eastern Oregon and Washington Province boundary is shown in yellow (Brownfield, 2008). Location of the Coos Bay coal field shown as a solid brown oval, and the Mist gas field shown as a solid red circle.

of uncertainty about the presence of suitable reservoirs and source rocks. Three unconventional (coalbed gas) plays were also assessed, Western Washington-Bellingham Basin (0450), Western Washington-Western Cascade Mountains (0451), and Western Washington-Southern Puget Lowland (0452).

For the eight conventional petroleum plays assessed in Province 4 (Johnson and Tennyson, 1995), a mean undiscovered hydrocarbon resource of 590 BCFG and 19.3 million barrels of oil (MMBO) was estimated. Mean estimated undiscovered gas resource from the three hypothetical coalbed-gas plays was 697.3 BCFG.

This new assessment of the Western Oregon and Washington Province was geology based, and the total petroleum system (TPS) concept was applied. The geologic elements of a TPS include hydrocarbon source rocks (source rock maturation and hydrocarbon generation and migration), reservoir rocks (quality and distribution), and traps for hydrocarbon accumulation. Using these geologic criteria, the USGS defined three TPSs and two conventional assessment units (AU) and one continuous AU. The Cretaceous-Tertiary Composite and the Tertiary Marine TPSs contain the Western Oregon and Washington Conventional Gas and the Tertiary-Marine Gas AUs, respectively. The Tertiary Coalbed Gas TPS contains the continuous Eocene Coalbed Gas AU. Undiscovered hydrocarbon resources were assessed in each of the defined AUs.

Geologic Setting of Western Oregon and Washington Province

The Western Oregon and Washington Province (fig. 1) occupies a complex geologic setting along the northwestern continental margin of North America (figs. 2 and 3). The region overlies a major north-trending crustal boundary between the pre-Tertiary terranes of the Cascade and Klamath Provinces and the mafic basement of the Oregon and Washington Coast Range (Eocene Crescent Formation and Siletz River Volcanics). The boundary fault between these terranes is exposed in two places: the southern part of Vancouver Island where the Leach River thrust fault is the crustal boundary and the southwestern part of Oregon where the Wildlife Safari fault is the boundary (fig. 4). The eastern boundary fault likely is buried beneath the Puget Lowland and the Willamette Valley (fig. 2).

Rocks accreted during pre-Tertiary subduction crop out around the margins of the province in the north Cascade Range, San Juan Islands, and Klamath Mountains and probably underlie much of the Paleogene rocks in the eastern part of the province (figs. 2, 3, and 4). They include ultramafic rocks, mafic volcanic rocks, graywacke, mudstone, chert, and plutonic and metamorphic rocks and are considered unlikely to be prospective for hydrocarbons.

Basement rocks for the western part of the province (the Coast Range block) consist of a thick complex of Paleocene to Eocene mafic submarine volcanic rocks consisting of the Crescent Formation of northwestern Washington and the Siletz River Volcanics of the Oregon Coast Range (figs. 3 and 4). These rocks are now widely believed to have formed in a continental-margin rift setting (Wells and others, 1984; Snavely, 1987; Babcock and others, 1992). In the Olympic Peninsula of western Washington, the thick submarine basalt of the Crescent Formation is structurally underlain by a subducted Eocene to Miocene melange complex consisting of the Ozette terrane (Snavely and others, 1993b) and the Hoh rock assemblage (Rau, 1973) that record ongoing subduction through Cenozoic time (fig. 5). Similar rocks are inferred at depth beneath the entire continental margin of Washington and Oregon.

Throughout the province, Cenozoic forearc-basin strata, as much as 20,000 ft thick, onlap the diverse pre-Tertiary basement and the Paleocene to Eocene volcanic basement. Forearc deposition occurred in a wide range of settings, including fluvial, fan-delta, delta, shallow-marine, continental-slope, and submarine-fan environments. The lower part of this sequence is interbedded with, and intruded by, Eocene volcanic rocks. The strata show general patterns of progradation northward from a southern Klamath igneous and metamorphic source and westward from both volcanic source terranes in the Cascade Range and distant crystalline rocks in northeastern Washington, eastern Oregon, and Idaho. Sandstones derived from the more distant crystalline terranes typically are Eocene in age and are more promising as reservoir rocks because they are less susceptible to diagenetic deterioration of porosity and permeability by alteration of unstable volcanic lithic grains. Such sandstone units include parts of the shallow marine Spencer and Cowlitz Formations, the deltaic Coaledo Formation, several members of the deltaic to submarine fan or ramp Tyee Formation, the fluvial Chuckanut Formation, and parts of the deltaic Puget Group (fig. 5; also see fig. 8). During the Eocene, the region was deformed by oblique subduction along the continental margin, as well as extension and clockwise rotation of the Coast Range block (fig. 3). This Eocene deformation caused widespread and heterogeneous folding, faulting, uplift, and subsidence. The upper middle and upper Eocene coal-bearing rocks crop out in the western foothills of the Cascade Range, on the eastern flank of the Puget Lowland, and in Chehalis Basin and Willamette Valley (fig. 2).

Oligocene strata generally record a westward progradation of the coastline, have a significant volcaniclastic component, and are not generally prospective for petroleum. Uplift of most of the Oregon Coast Range of the Oregon part of the forearc basin and Washington’s Olympic Mountains took place in Oligocene to Pliocene time, while local depositional centers such as the Grays Harbor Basin of southwest Washington continued to subside.

Formation of the Cascade volcanic arc began in the late Eocene to early Oligocene. Quaternary volcanoes in the Pacific Northwest include Mount Adams, Mount Baker, Mount Rainier, Mount Hood, Mount Jefferson, and the recently active Mount St. Helens (fig. 3).

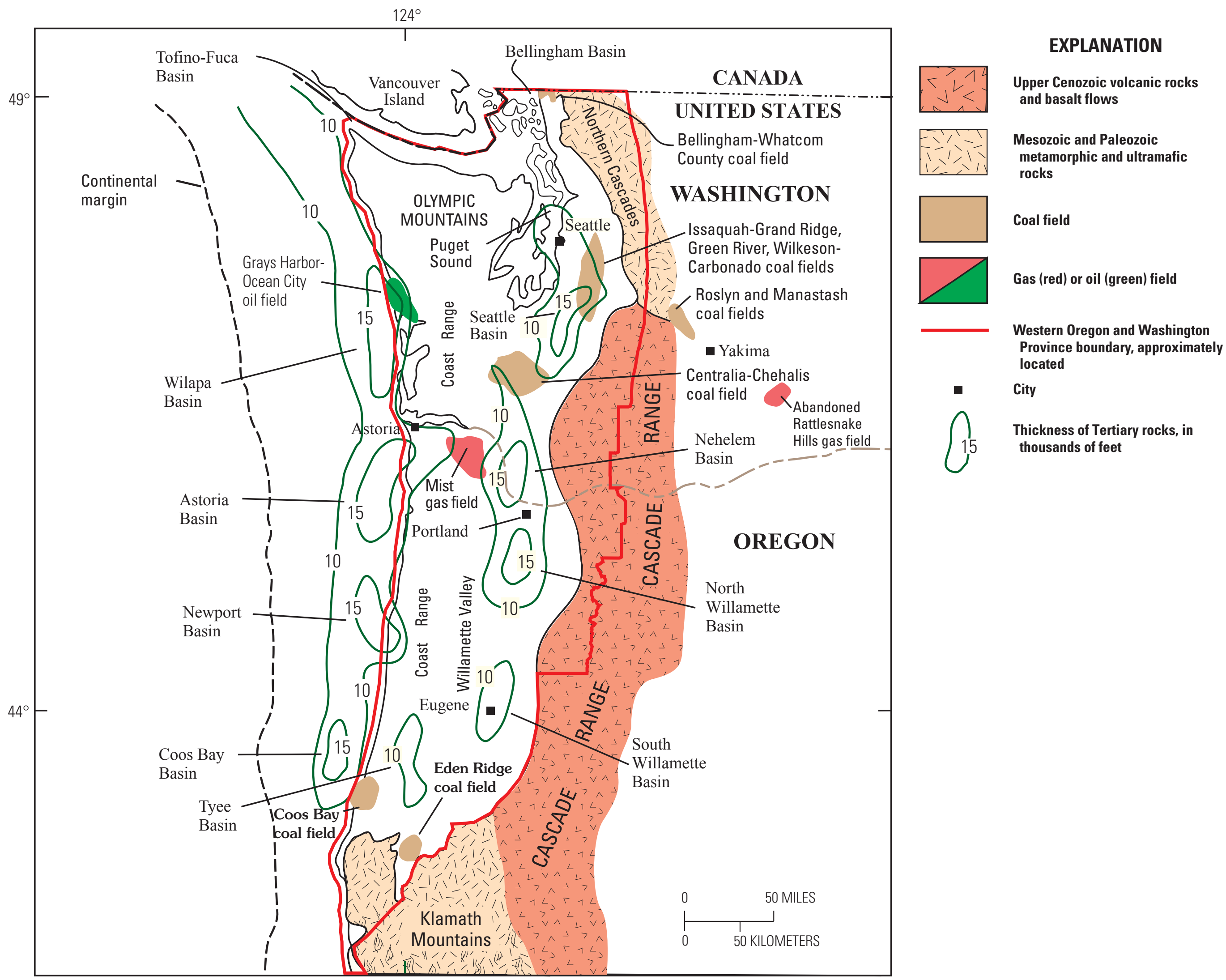

Figure 2. Locations of selected Tertiary basins in the Western Oregon and Washington Province (red outline), and the approximate locations of oil and gas fields and Eocene coal fields. Isopach contours of Tertiary rocks are in thousands of feet. Modified from Braislin and others (1971), Snavely and Wagner (1980), and Armentrout and Suek (1985).

In middle and late Miocene time, flood basalt of the Columbia River Basalt Group erupted in eastern Washington and Oregon. Huge volumes of basalt repeatedly surged down the course of the Columbia River, ponding in the floor of the northern part of the Willamette Valley and continuing on to the Pacific Ocean. These basalt flows built lava deltas and invaded the continental margin strata as voluminous sills and other intrusive bodies, possibly contributing to heating of potential petroleum source rocks in the pre-middle Miocene section.

During Miocene and Pliocene time, the ancestral Columbia River deposited large volumes of shallow marine and deltaic sediments in what is now coastal southwestern Washington and northwestern Oregon (Astoria and Montesano Formations), supplemented by smaller coastal river systems. Late Cenozoic deformation, continuing today, has involved gentle folding, rapid uplift of the Olympic Mountains, and both reverse and strike-slip faulting.

During the Pleistocene, alpine glaciers occupied parts of both the Cascade Range and the Olympic Mountains. The Puget Lowland, an elongate topographic trough between these two highlands, was occupied by a lobe of the continental ice sheet. The Puget Lowland is now mantled by unconsolidated glacial deposits of variable thickness.

Figures 6 and 7 are generalized geologic maps of the western parts of Oregon (modified after Walker and MacLeod, 1991; and Walker and others, 2003) and Washington (modified after Schuster, 2005).

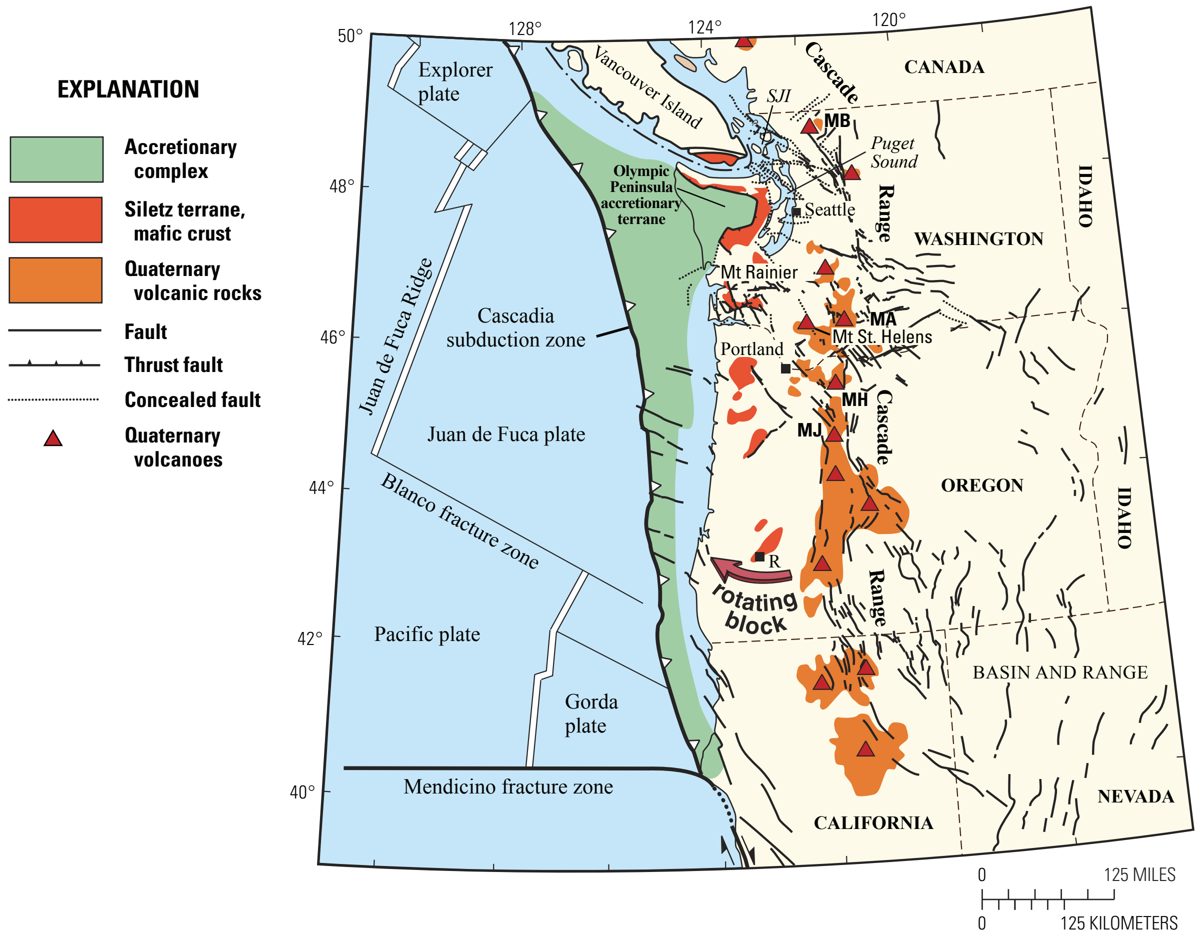

Figure 3. Generalized geologic map showing the major tectonic elements of the Cascadia subduction zone in the Pacific Northwest. The accretionary complex (green) broadens northward along the margin, reaching its widest point at the Olympic Mountains. Volcanic activity is greatest in the central part of the Cascade Range. MA, Mount Adams; MB, Mount Baker; MH, Mount Hood; MJ, Mount Jefferson; R, Roseburg; SJI, San Juan Islands. Modified after Parsons and others (2005).

Western Oregon

The western Oregon part of the province is bounded on the south by the northern margin of the pre-Tertiary Klamath Mountains and on the east by upper Eocene to Quaternary arc-related volcanic rocks of the Cascade Range (fig. 2) and extends offshore to the 3-mile limit of State waters on the west. The northern boundary is the Columbia River.

Siletz River Volcanics

The basement rocks of western Oregon consist of Paleocene to lower Eocene marine basalts and volcaniclastic rocks of the Siletz River Volcanics (figs. 8 and 9), which are as much as 19,700 ft thick (Wells and others, 2000) in the southern part of the Oregon Coast Range. Based on seismic studies (Trehu and others, 1994), the Siletz River Volcanics forms a continuous basement unit beneath the Oregon coastal region and the Willamette Valley ranging from 15.5 to 22 mi thick in the central part of the Coast Range; equivalent rocks thin to about 3.7 mi thick near Vancouver Island (Trehu and others, 1994). The Siletz River Volcanics, also known as the Siletz terrane, are thought to represent an oceanic plateau, an island chain, or a marginal basin that was accreted to the North American continent in the early Eocene (Simpson and Cox, 1977; Duncan, 1982; Wells and others, 1984; Clowes and others, 1987; Snavely, 1987; Babcock and others, 1992; Wells and others, 2000).

The Siletz River Volcanics, in the southern part of the province, consists of two submarine lithofacies. The first lithofacies is located mostly in the southern part of the Oregon Coast Range near Roseburg (figs. 3, 8, and 9), which consists of massive to pillowed basalt (fig. 10), pillow breccia, lapilli tuff, laminated tuff, basaltic sandstone, and mudflow

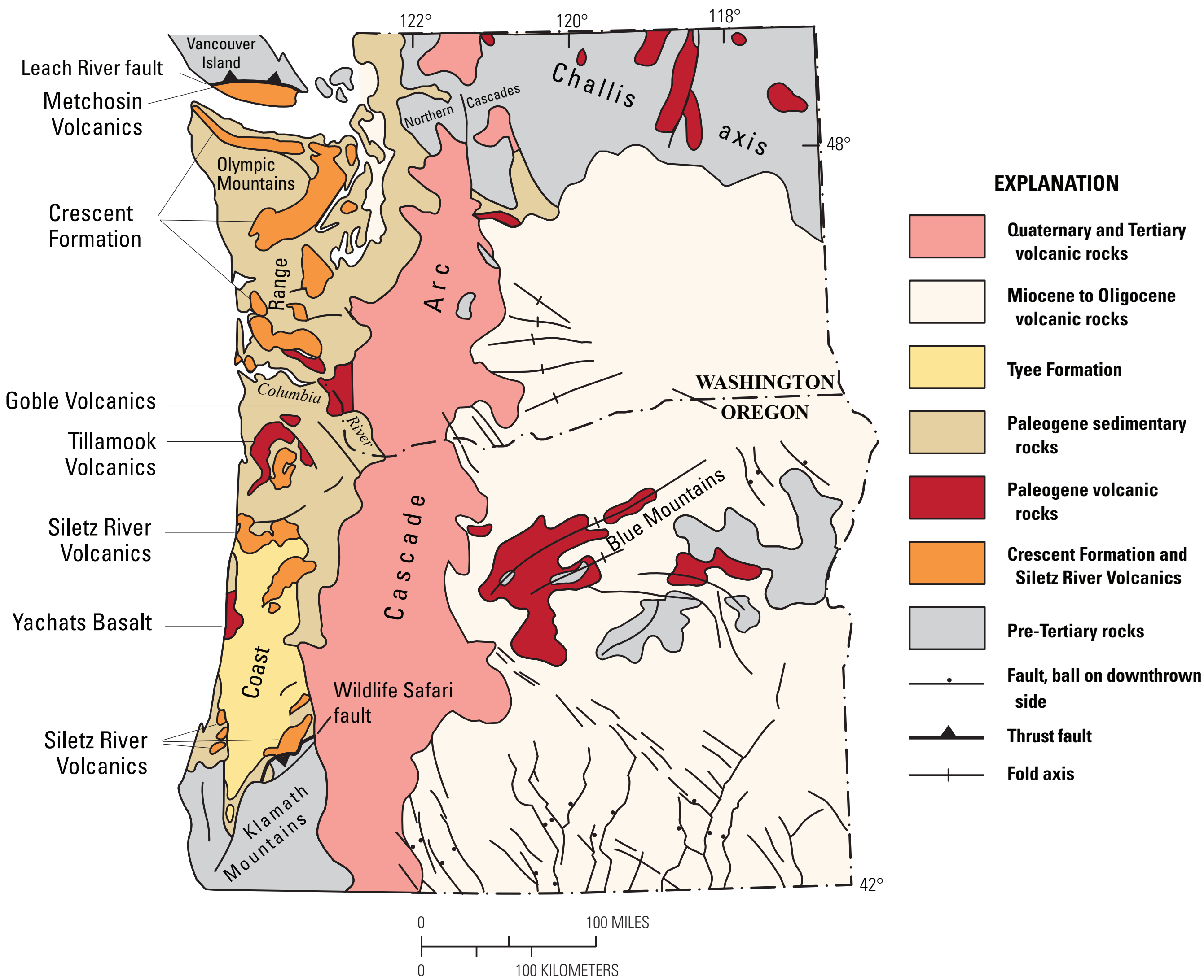

Figure 4. Generalized geologic and tectonic features of Oregon and Washington. The Wildlife Safari fault is the major suture or boundary fault between the Oregon Coast Range terranes and the Upper Jurassic–Lower Cretaceous accretionary terranes in Oregon. The Leach River fault is the boundary fault between the Olympic Mountains and the Washington Coast Range terranes and the pre-Tertiary terranes in Washington. Modified after Wells and others (1984).

breccia, with minor turbidite sandstone and mudstone (fig. 11), sandstone, and conglomerate interbeds (Molenaar, 1985; Wells and others, 2000). The turbidite interbeds contain clasts and rock fragments that appear to be derived from the Klamath Mountains, indicating that the basalts and associated volcaniclastic rocks were likely extruded near the Juan de Fuca-North American plate margin (fig. 3). The second lithofacies exposed north of Roseburg (fig. 9) consists of flow basalt and breccia and minor sedimentary interbeds. The age of the Siletz River Volcanics in the southern Oregon Coast Range is determined from microfauna in the sedimentary interbeds (Baldwin, 1974, 1975; Wells and others, 2000) and the sequence was mapped as the Roseburg Formation (fig. 12) by Baldwin (1974).

In the type locality, in the central part of the Oregon Coast Range, the Siletz River Volcanics contains marine tholeiitic basalt flows, pillow basalt, flow breccia, and volcaniclastic rocks (Snavely and Baldwin, 1948; Beaulieu, 1971) of early and middle Eocene age (Snavely and Wagner, 1963; Duncan, 1982). Minor tuffaceous siltstone interbeds are locally present. The Kings Valley Siltstone Member of the Siletz River Volcanics (fig. 8) is about 3,000 ft thick and overlies the main volcanic unit (Vokes and others, 1955); the member consists of thinly bedded tuffaceous siltstone and

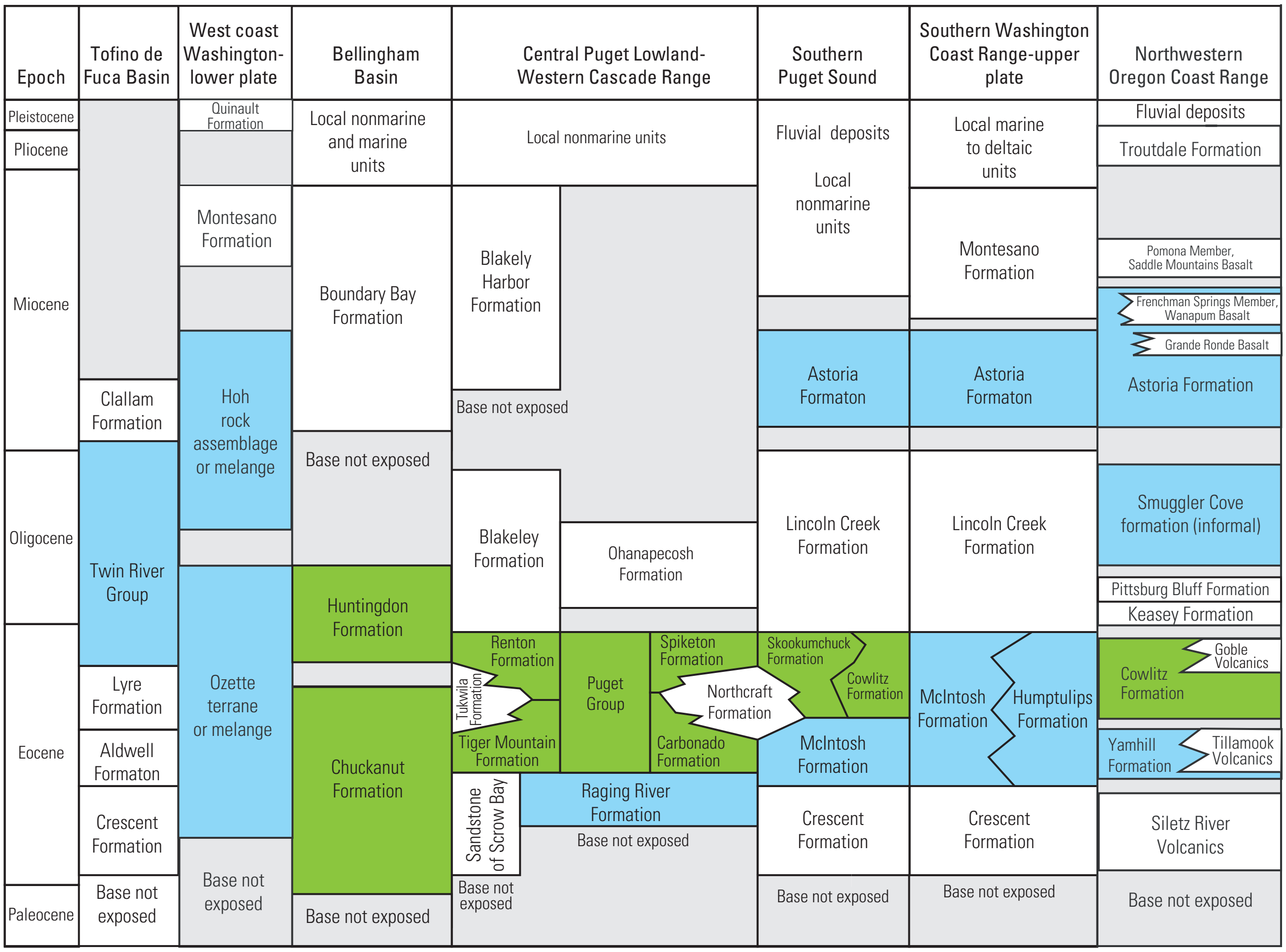

Figure 5. Stratigraphic correlation chart for the northern part of western Oregon and western Washington showing selected Tertiary units. Light gray shading indicates intervals of erosion or nondeposition. Coal-bearing units are highlighted in green. Marine units containing possible source rocks are highlighted in blue. Modified after Braislin and others (1971), Armentrout and Suek (1985), and Johnson and others (1997).

water-laid tuff, and likely represents a late pyroclastic phase in Siletz River volcanism.

Umpqua and Tyee Basins, Oregon Coast Range

Two superimposed basins with different regional trends are recognized in the southern Oregon Coast Range (figs. 8, 9, and 13) (Ryu and others, 1992; Ryu, 1995; Ryu and Niem, 1999; Ryu, 2008). The Paleocene to early Eocene Umpqua Basin is northeast-trending, and is filled with strongly deformed turbidite rocks of the Umpqua Group (fig. 12). Superimposed on the Umpqua Basin is the Tyee forearc basin (figs. 9 and 13) (Snavely and others, 1964; Chan, 1985; Heller and Ryberg; 1983, Ryu and others, 1992; Ryu and Niem, 1999; Wells and others, 2000; Ryu, 2008). The Tyee Basin is less deformed and filled with the lower to middle Eocene Tyee Formation and middle to upper Eocene Elkton, Bateman, and Spencer Formations (fig. 13). The lower part of this Cenozoic forearc sequence is interbedded with pillow basalt of the Siletz River Volcanics and intruded by Eocene volcanic rocks. Paleogene forearc-basin strata onlap the diverse pre-Tertiary basement rocks of the Klamath Mountains and the Paleocene to Eocene volcanic basement (fig. 13). The overall thickness of sedimentary rocks in the Umpqua-Tyee Basins is about 23,000 ft in the southern part of the Oregon Coast Range (Ryu and Niem, 1999; Ryu, 2008). Deposition occurred in a range of settings, including fluvial, fan-delta, delta, shallow-marine, continental-slope, and submarine-fan environments (fig. 14); these strata overlap the Siletz terrane in the Oregon Coast Range and unconformably overlie rocks in the Klamath Mountains.

The Umpqua Basin strata represent a partially subducted accretionary wedge deposited either on a rifting continental margin (Wells and others, 1984) or in a trench (Heller and

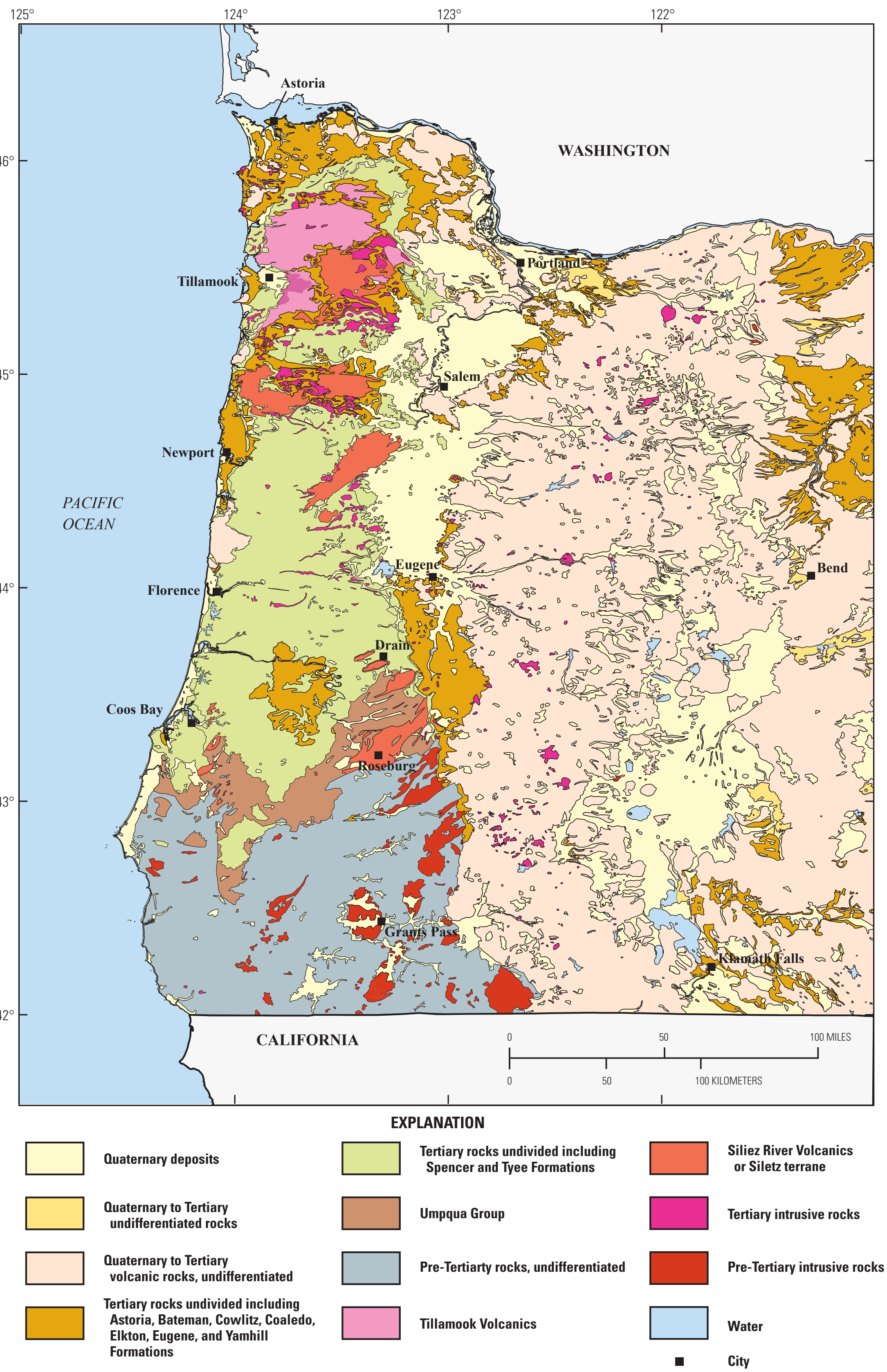

Figure 6. Generalized geologic map of the western part of Oregon. Modified from Walker and MacLeod (1991) and Walker and others (2003).

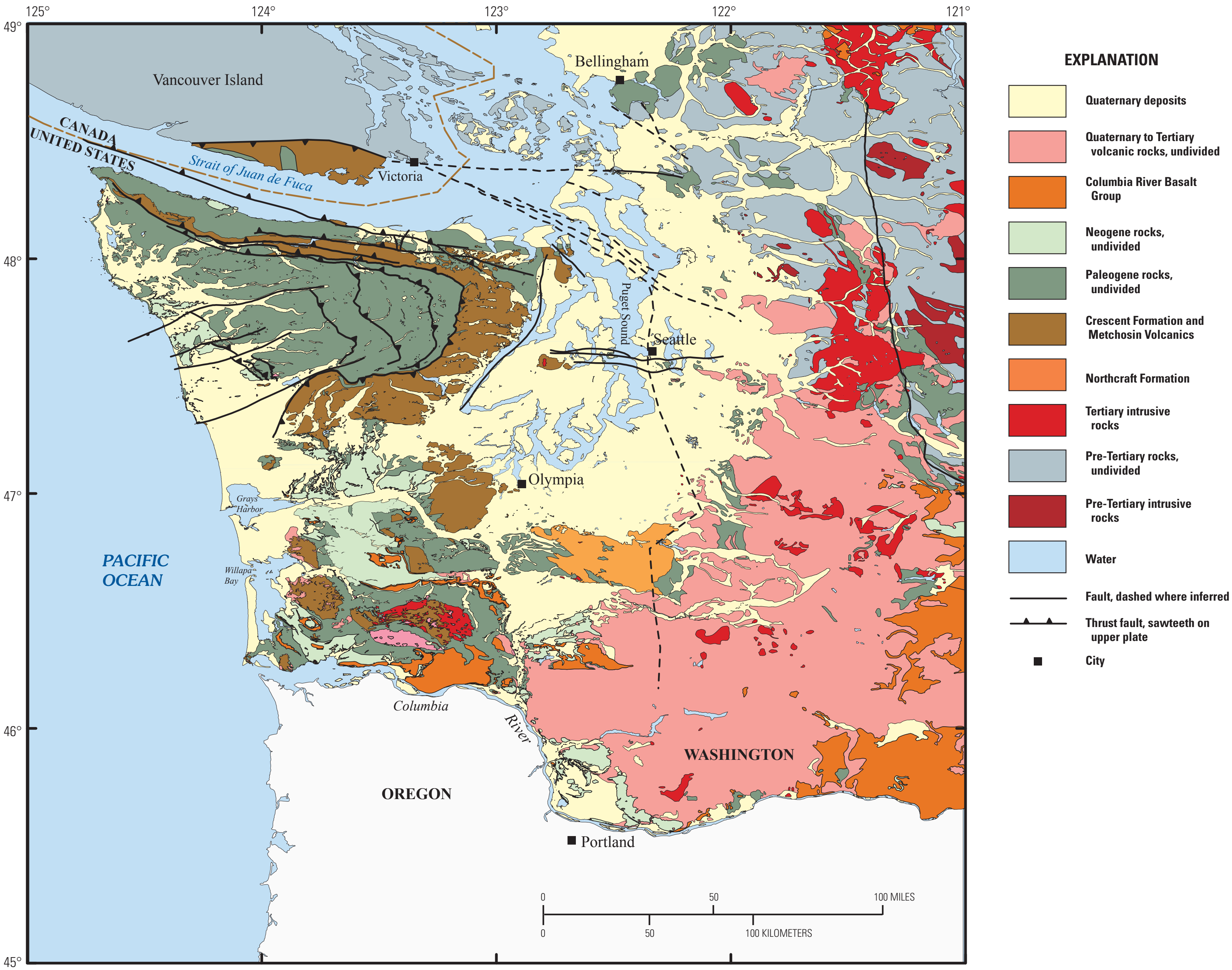

Figure 7. Generalized geologic map of the western part of Washington and the southern part of Vancouver Island. Modified after Schuster (2005).

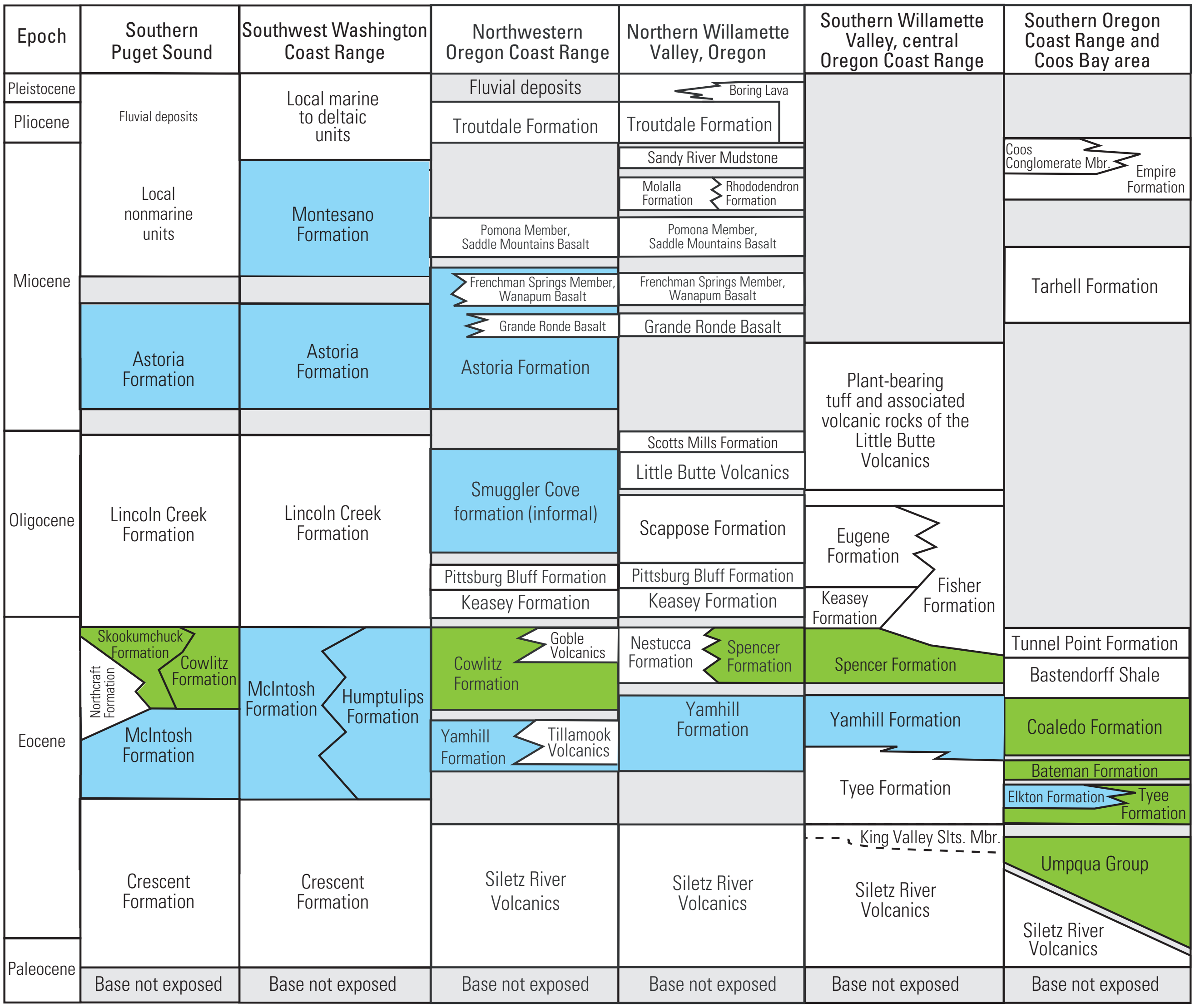

Figure 8. Stratigraphic correlation chart for western Oregon and southern part of western Washington showing selected Tertiary units. Light gray shading indicates intervals of erosion or nondeposition. Coal-bearing units are highlighted in green. Marine units containing possible source rocks are highlighted in blue. Modified after Braislin and others (1971), Armentrout and Suek (1985), Orr and others (1992), Johnson and others (1997), and Wells and others (2000).

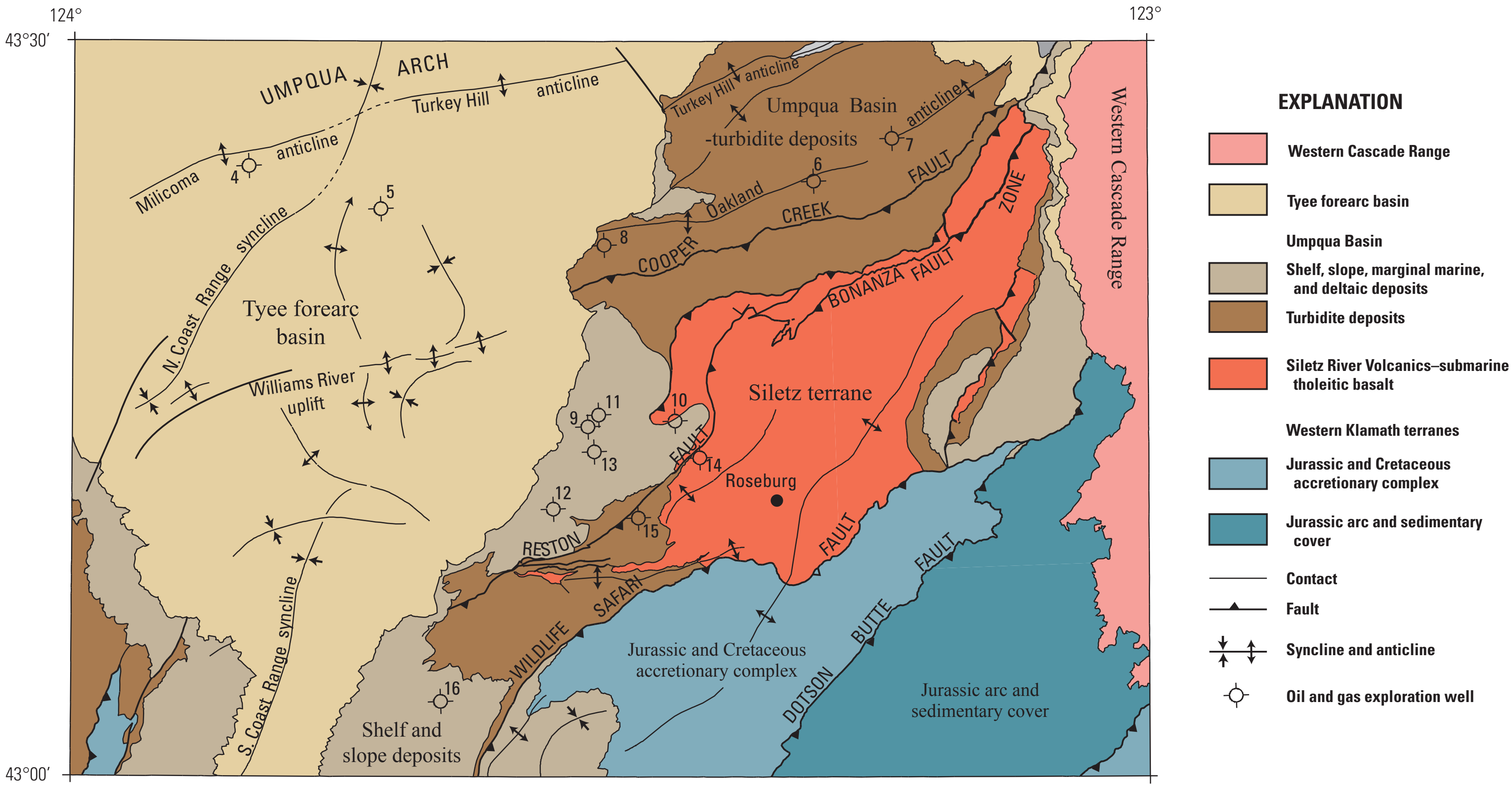

Figure 9. Generalized geologic map and tectonic features of the Roseburg 1:100,000-scale 30′ × 60′ quadrangle with oil and gas exploration wells (shown in table 1), southwestern Oregon. The Wildlife Safari fault is the major suture or boundary fault between the Oregon Coast Range terranes and the Upper Jurassic-Lower Cretaceous accretionary terranes of North America. See figure 4 for the northern boundary fault on Vancouver Island. Modified after Wells and others (2000).

Figure 10. Outcrop of massive pillow basalt in the Paleocene to lower Eocene Siletz River Volcanics west of Roseburg, Oregon (see fig. 9). Note 12-in. hammer for scale.

Figure 11. Turbidite beds in the Siletz River Volcanics northwest of Roseburg, Oregon (see fig. 9).

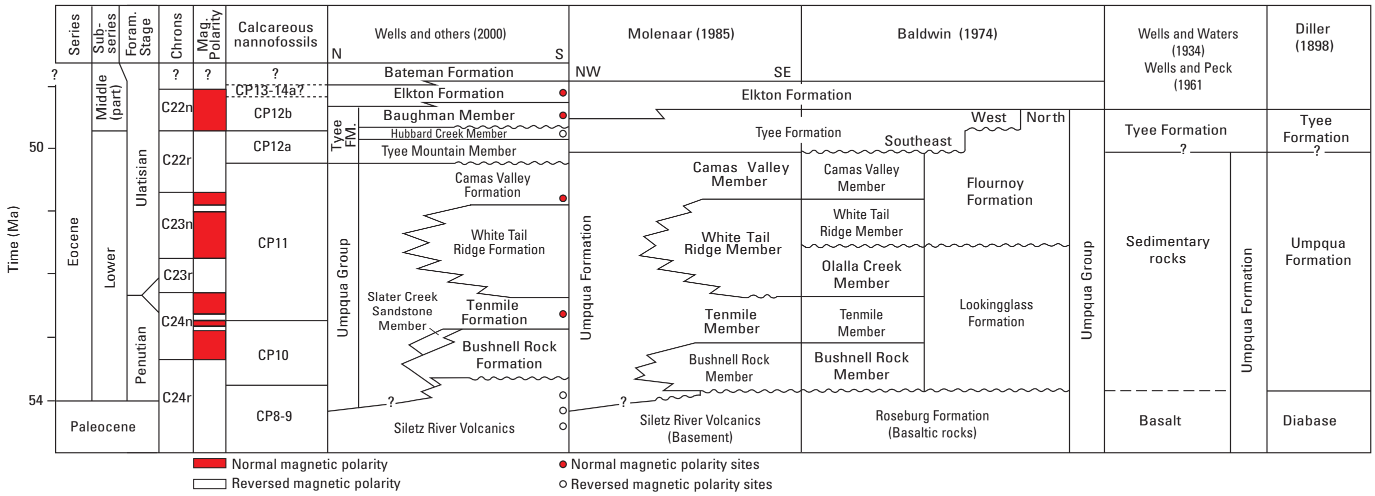

Figure 12. Stratigraphic nomenclature chart for the southern part of the Oregon Coast Range. Modified from Wells and others (2000)

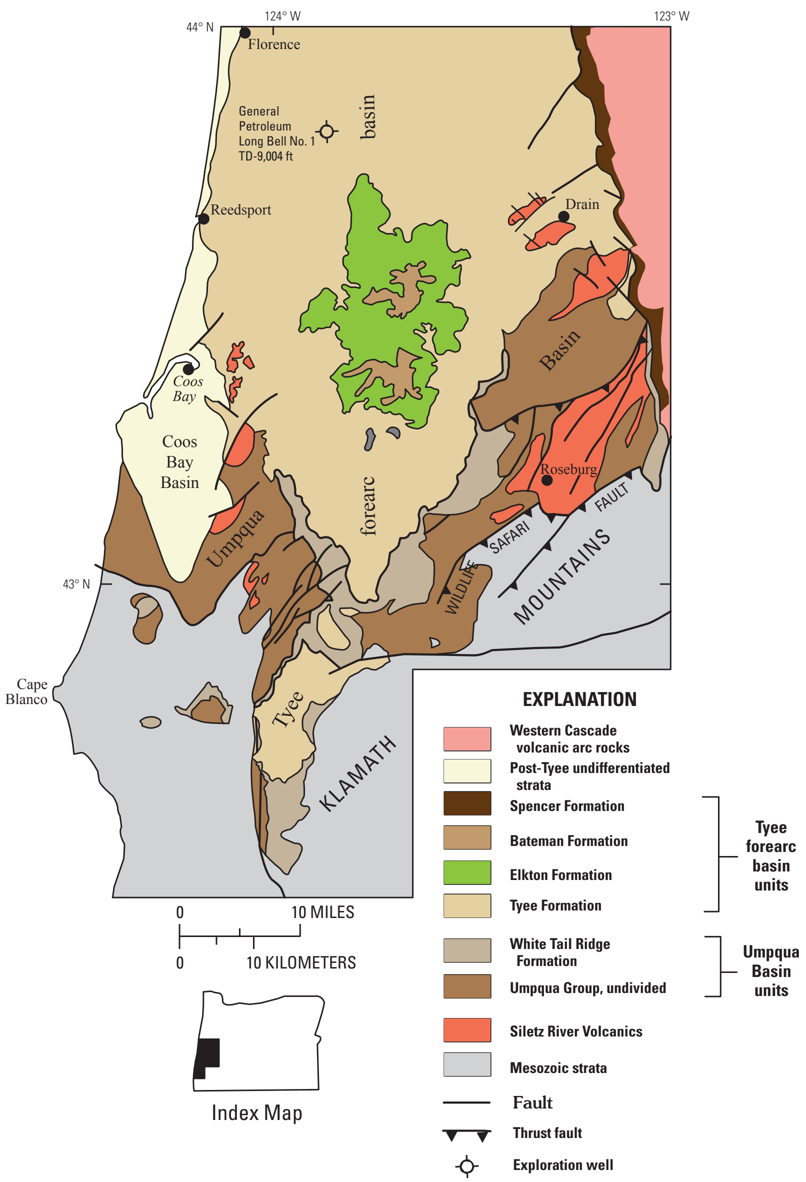

Figure 13. Generalized geologic map showing the Eocene Umpqua Basin, the middle Eocene Tyee forarc basin, and the upper Eocene to Miocene Coos Bay Basin of the southern part of the Oregon Coast Range. Note the northeast–southwest structural trend of the lower Eocene Umpqua Basin strata in fault contact with Paleocene to lower Eocene Siletz River Volcanics basement and Mesozoic terranes of the Klamath Mountains. Middle Eocene strata of the Tyee forearc basin and upper Eocene to middle Miocene strata of the Coos Bay Basin display a north–south trend that is discordant with the early Eocene trend. Modified after Ryu and others (1996).

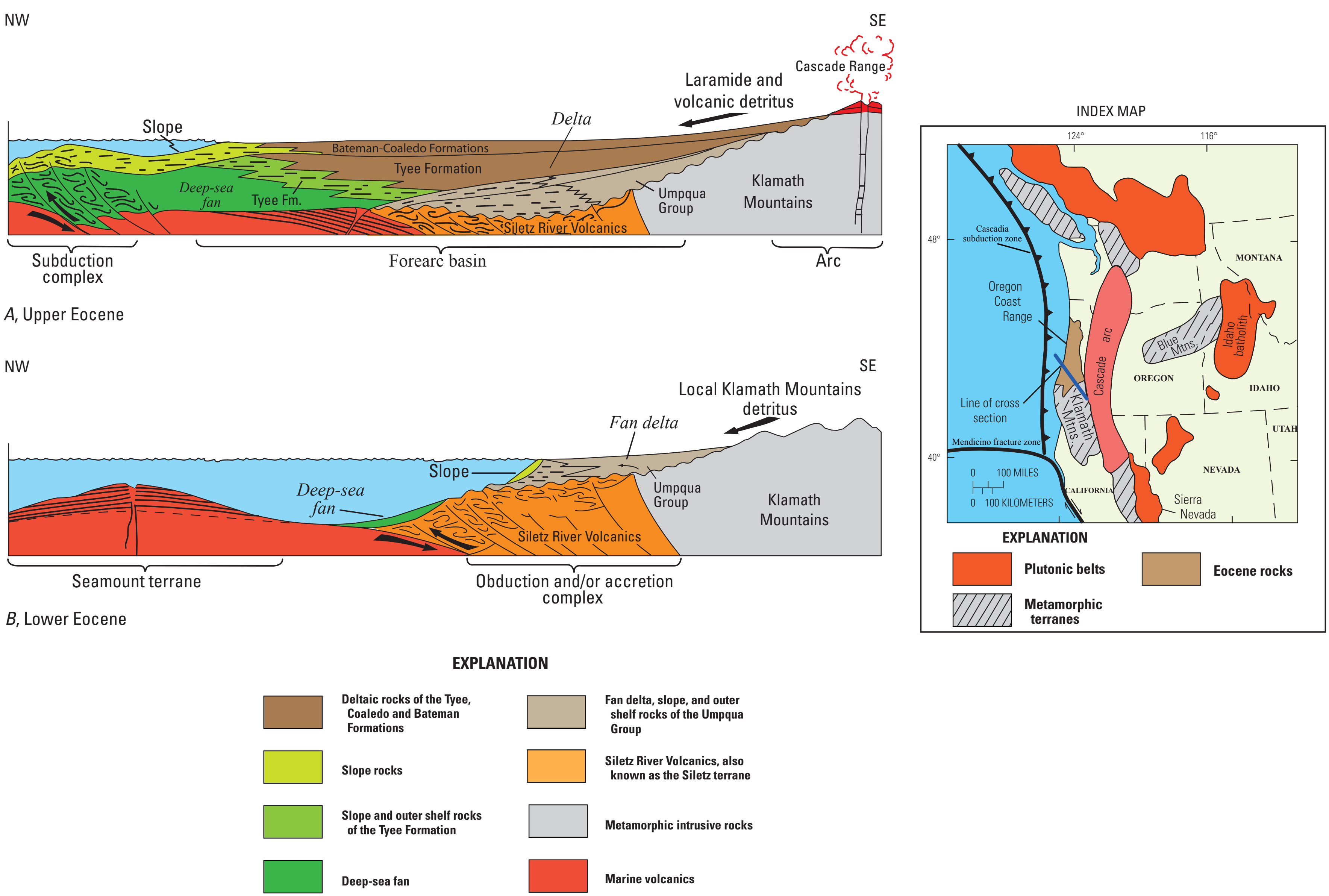

Figure 14. Diagrammatic cross sections of southern Oregon Coast Range and Klamath Mountains lower Eocene and upper Eocene depositional systems showing (*A*) subduction-zone sedimentation during accretion of the Siletz River Volcanics and (*B*) post-accretion forearc sedimentation. Modified after Heller and Ryberg (1983) using the Eocene stratigraphy revisions of Molenaar (1985) and Wells and others (2000).

Ryberg, 1983).The stratigraphic nomenclature has undergone many changes from the late 1890s (fig. 12), with both the Umpqua Formation and the Umpqua Group names being used; this paper adopts the stratigraphic nomenclature of Wells and others (2000) as shown in the left-hand column of figure 12. The Umpqua Group is at least 10,000 ft thick (Molenaar, 1985). Syntectonic fan-delta and marginal-marine lithic sediments were deposited along the southernmost margin of the Oregon Coast Range as the Bushnell Rock Formation of the Umpqua Group (Wells and others, 2001) and the Slater Creek Sandstone Member of the Bushnell Rock Formation (figs. 12 and 15). The Bushnell Rock Formation consists mostly of conglomerate (fig. 15), consisting of boulder to pebble clasts derived from the Klamath Mountains. Depositional environments include fanglomerate, fan delta, and deep marine turbidite channels that interfinger upsection with thick-bedded, fine-grained sandstone of the Slater Creek Sandstone Member. Overlying the Bushnell Formation and Slater Creek Member is the Tenmile Formation (fig. 12), which has been interpreted as trench-fill turbidites deposited on the Siletz River Volcanics. The transgressive Tenmile Formation consists of deep-marine inner, middle, and outer submarine-fan turbidite sandstones (fig. 16) and basinal mudstones in a marginal basin or trench setting (Heller and Ryberg, 1983; Niem and Niem, 1990; Ryu and Niem, 1999; Wells and others, 2000). Subduction ceased along the trench after the deposition of the Tenmile Formation resulting in development of seamounts. The fluvial to deltaic lithic strata of the overlying White Tail Ridge Formation (fig. 17) filled irregular lows between the seamounts and thinned over submarine highs (Ryu and Niem, 1999). The White Tail Ridge locally contains carbonaceous mudstones and coal. The uppermost formation of the Umpqua Group is the Camas Valley Formation (fig. 12), which consists of thick, concretionary, foraminifer-bearing dark-gray mudstone that was deposited in a slope environment.

West of the Roseburg area and east and south of the Coos Bay Basin in the Oregon Coast Range (figs. 6 and 13), the Umpqua Group cannot be differentiated into individual formations (Molenaar, 1985). South of Coos Bay Basin, the sequence consists of thick mudstone and turbidites, and west and north of Coos Bay, it is absent due to depositional thinning across structural highs or seamounts within the Siletz terrane.

The Eocene Tyee forearc basin extends north–south about 200 mi and is overlapped on the east by Tertiary volcanic rocks of the Cascade Range and bounded on the south by the Mesozoic Klamath Mountains (figs. 6 and 13). The basin contains about 23,000 ft of strata deposited in the active North American convergent margin (Ryu, 2003) and records a change from the Umpqua Group in deformation style and provenance. During the late early Eocene, a new subduction zone developed west of the present continental margin forming a magmatic arc in central Oregon west of the Blue Mountains where the volcanic rocks of the Clarno Formation were deposited (see index map, fig. 14). Arkosic and volcaniclasic sediments from the Idaho batholith and Clarno volcanic arc were deposited in the Tyee forearc basin (Heller and Ryberg, 1983).

In the southern part of the Tyee Basin, the lower to middle Eocene Tyee Formation (fig. 12) is about 10,000 ft thick and is subdivided into three members in the southern Oregon Coast Range: the Tyee Mountain, Hubbard Creek and Baughman Members (Ryu and others, 1996; Wells and others, 2000). The Tyee Mountain Member (fig. 18) ranges in thickness from about 3,000 to 6,560 ft and consists of thick, fine-grained, micaceous, rhythmically bedded sandstone; lithic arkosic sandstone; and mudstones deposited as turbidites in a forearc basin (Heller and Ryberg, 1983). The Hubbard Creek Member, 600 to 1,600 ft thick, consists of thin-bedded, micaceous, gray siltstone and turbidite channel sandstones that have been interpreted as slope deposits (Ryu and others, 1992). The deltaic to fluvial Baughman Member (fig. 19) is a thick-bedded, micaceous, crossbedded arkosic sandstone and gray mudstone ranging in thickness from 2,000 to 2,500 ft (Baldwin, 1974; Ryu and others, 1996) and contains three to four thickening-upward cycles in the deltaic facies (Wells and others, 2000). The Baughman Member contains minor carbonaceous mudstone and coal.

In the central, northern, and western parts of the Tyee Basin, the Tyee Mountain and Baughman Members cannot be differentiated where the intervening Hubbard Creek Member is missing; in those areas, the Tyee Formation is recognized only as a single unit (fig 12). The Tyee turbidites northeast of Newport, Oreg., are observed in outcrop as either thick-bedded, graded, medium- to fine-grained lithic arkosic turbidite sandstones (fig. 20) or as more distal rhythmically bedded turbidites consisting of sandstone and mudstone units (fig. 21).

Figure 15. Outcrop of conglomerate in the Bushnell Rock Formation of the Umpqua Group (see fig. 12) near Lookingglass, Oregon, west of Roseburg, Oregon (see fig. 9). Note 3.25-in. knife for scale.

Figure 16. Outcrop images of the Tenmile Formation of the Umpqua Group (see fig. 12), southern Oregon Coast Range. *A*, Outcrop of strongly folded turbidite beds in the Tenmile Formation northwest of Roseburg, Oregon (see fig. 9). *B*, Strongly folded turbidite beds in the Tenmile Formation along the Umpqua River northwest of Roseburg, Oregon (see fig. 9).

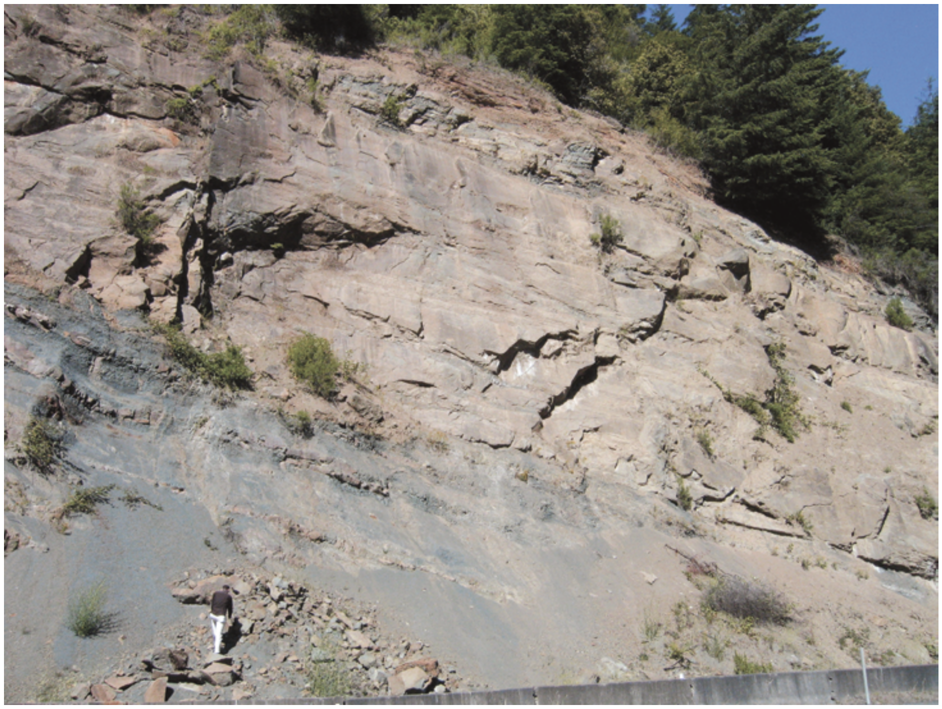

Figure 17. Outcrop of the White Tail Ridge Formation of the Umpqua Group (see fig. 12) along Oregon Route 42 west of Roseburg, Oregon (see figure 9).

Figure 18. Tyee Mountain in the southern part of the Oregon Coast Range, northwest of Roseburg, Oregon (see figs. 6 and 9). Massive cliff-forming sandstone units are turbidites in the Tyee Mountain Member of the Tyee Formation (see fig. 12).

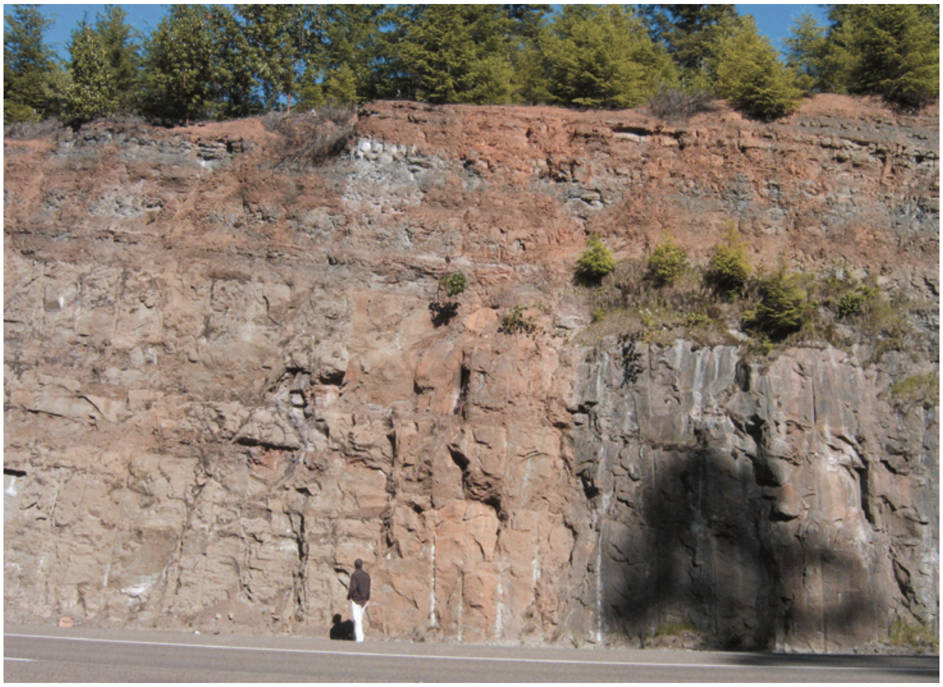

Figure 19. Exposure of cliff-forming, thick-bedded, lithic arkosic sandstone in the Baughman Member of the Tyee Formation (see fig. 12), southern Oregon Coast Range in road cut along Oregon Route 42 west of Roseburg, Oregon (see figs. 6 and 9).

Overlying the Tyee Formation is the middle Eocene Elkton Formation (fig. 12), consisting of up to 1,600 ft of mudstone that was deposited in a slope environment (Ryu and Niem, 1999; Ryu, 2003). The Elkton Formation interfingers with the underlying Baughman Member of the Tyee Formation in the Roseburg area (Wells and others, 2000), and is overlain by the middle and upper Eocene wave- to tide-dominated deltaic Bateman Formation (fig. 8). The Bateman Formation contains delta-front, distributary mouth bar, and distributary channel units. The delta-front facies ranges from 100 to 200 ft thick and consists of micaceous feldspathic sandstone with interbeds of burrowed siltstone and carbonaceous mudstone and coal (Ryu and others, 1992; Ryu, 2008).

Yamhill Formation

The middle to upper Eocene Yamhill Formation unconformably overlies the Siletz River Volcanics in the north-central Oregon Coast Range (fig. 8); it is interbedded with the upper middle Eocene Tillamook Volcanics (Wells and others, 1994) and overlies and might be interbedded with Tyee Formation. Baldwin and others (1955) reported a thickness as much as 6,500 ft at the type locality along Mill Creek in the Sheridan, Oregon, 1:62,500-scale quadrangle (Baldwin and others, 1955). The Yamhill Formation (fig. 22) ranges from 3,000 to about 5,000 ft thick west of Salem, Oreg. (fig. 6), in the Sheridan and Grand Ronde 1:24,000-scale quadrangles, where it consists of massive to thin-bedded concretionary marine siltstone and thin interbeds of arkosic, glauconitic, and basaltic sandstone and, locally, contains interbedded basalt lava flows and lapilli tuff (Brownfield, 1982a,b). In the northern part of the Coast Range, thicknesses range from 1,000 to 2,000 ft. The basal part of the Yamhill Formation in the Dallas quadrangle, west of Salem, Oreg. (fig. 6), consists locally of impure shallow-water limestone beds, 40 to 100 ft thick (Baldwin, 1964; Boggs and others, 1973), which form a unit named the Rickreall Limestone Member of the Yamhill Formation by Baldwin (1964). In the northwestern part of the Oregon Coast Range, the upper part of the Yamhill Formation is basaltic and interfingers with basalt breccia and sandstone of the Tillamook Volcanics (fig. 5) (Wells and others, 1994). Foraminiferal assemblages in siltstone are representative of the Ulatisian and lower part of the Narizian Stages of the middle Eocene (Snavely and others, 1969; McNeal, 1980).

Cowlitz Formation

The Cowlitz Formation, of middle to late Eocene age, unconformably overlies the Yamhill Formation and the Tillamook Volcanics in the northern part of the Oregon Coast Range (fig. 5) (Armentrout and Suek, 1985). The type locality for the Cowlitz Formation, first described by Weaver (1912), is located in southwestern Washington where it consists of about 4,200 ft of marine, brackish-water, and nonmarine rocks with minor coal (Weaver, 1937). In northwestern Oregon, the Cowlitz Formation consists of as much as 1,000 ft of cross-bedded, micaceous, carbonaceous, fine- to medium-grained arkose and lithic arkose (fig. 23) with minor conglomerate, mudstone, and siltstone and is locally concretionary. Laminated thin-bedded mudstone and siltstone are interbedded in the upper part with minor volcanic flows, breccia, and tuffs . The Cowlitz Formation was deposited along a broad coastal plain and shelf margin that extended from Coos Bay in the south to Bellingham in the north (Dott, 1966; Buckovic, 1979;

Figure 20. Exposure of graded medium- to fine-grained arkosic sandstone turbidites with siltstone interbeds in the Tyee Formation in road cut along U. S. Route 20 east of Newport, Oregon (see fig. 6). Sandstone beds are 2 to 5 ft thick and the siltstone beds are 0.5 to 2 ft thick.

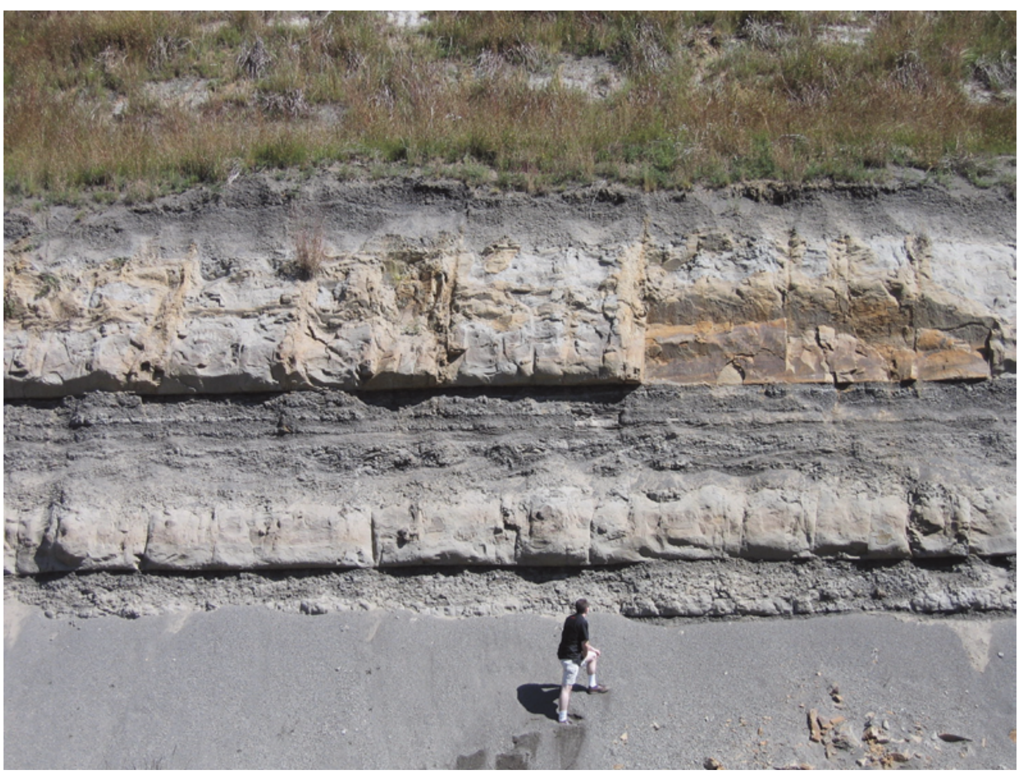

Figure 21. Outcrop of rhythmically bedded sandstone and siltstone turbidites of the Tyee Formation in road cut along U. S. Route 20 east of Newport, Oregon (see fig. 6)

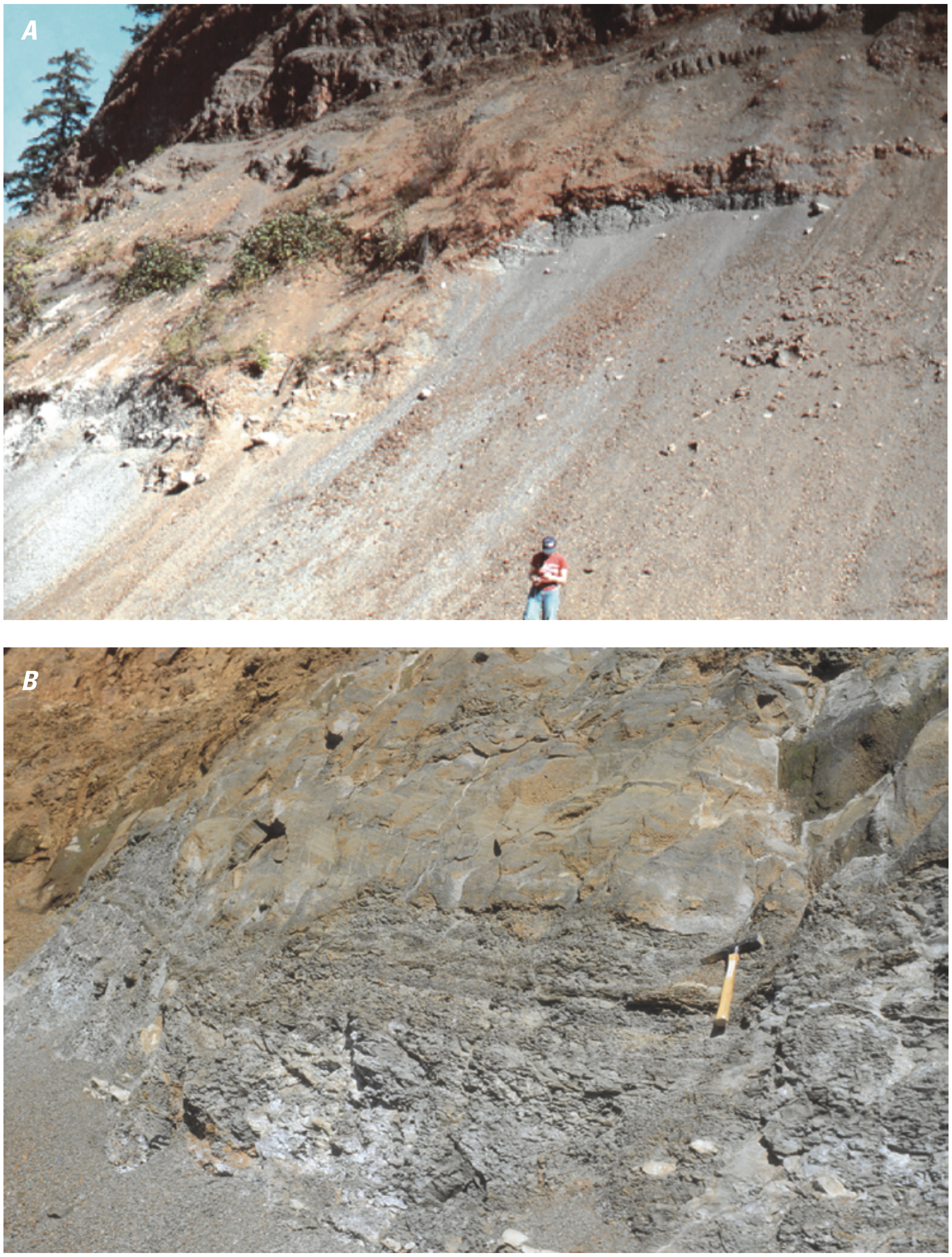

Figure 22. Outcrops of the middle to upper Eocene Yamhill Formation. *A*, Exposure of Yamhill overlain by volcanic rocks of the upper Eocene Nestucca Formation west of Salem, Oregon (see fig. 6). Photograph courtesy of Alan S. Niem. *B*, Exposure of Yamhill overlain by the upper Eocene Nestucca Formation (above 12-in. hammer) west of Salem, Oregon (see fig. 6).

Johnson, 1984a; Armentrout and Suek, 1985). The arkosic sands were transported from the east by river systems from the Idaho batholith of eastern Oregon and Washington. Local volcanic islands contributed the volcanic rock fragments to the sandstones. The interbedded volcanics are referred to as the Goble Volcanics (fig. 5) (Wilkinson and others, 1946; Alger, 1985); the upper part of the Tillamook Volcanics was added to this unit by Baldwin and others (1955). At the Mist field, Oregon's only producing gas field, the producing zones are in the shallow marine sandstone of the Cowlitz Formation. Newton and Van Atta (1976) reported that the Cowlitz foraminiferal assemblages are assigned to the upper part of the Narizian Stage of Mallory (1959).

Spencer Formation

The middle to upper Eocene Spencer Formation (figs. 6 and 8) crops out along the west side of the Oregon Coast Range from about 20 mi southwest of Portland to the Roseburg area where it unconformably overlies the Umpqua Group and is overlain by Cascade Range volcanic rocks (fig. 13) (Wells and others, 2000). In the central part of the Oregon Coast Range, the Spencer Formation unconformably overlies the Yamhill Formation (fig. 8) and in places is unconformably on the Tyee Formation (Beaulieu, 1971). The Spencer Formation consists of micaceous arkosic sandstone, carbonaceous siltstone and mudstone, and lignite and subbituminous coal.

Figure 23. Exposure of the middle to upper Eocene Cowlitz Formation sandstone beds in road cut along U.S. Route 26 west of Portland, Oregon. The Mist gas field produces gas from Cowlitz Formation reservoirs (see fig. 1).

Van Atta (1986) divided the Spencer Formation into two informal members, a lower member consisting of 800 to 1,000 ft of arkosic lithic sandstone and an upper member of siltstone and mudstone ranging in thickness from 1,000 to 1,300 ft; deposition occurred in neritic, nearshore, and nonmarine environments (Van Atta, 1986; Van Atta and Thoms, 1993). The Spencer Formation is 980 ft thick in the Roseburg area (Wells and others, 2000) and thickens to about 4,500 ft northwest of Eugene (Beaulieu, 1971) (figs. 6 and 8). In the northwestern part of the Willamette Valley, the sandy part of the Spencer is about 200 ft thick and is interbedded with mudstone and minor carbonaceous shale and coal (Schlicker, 1962); it then wedges out southwest of Portland (Beaulieu, 1971). The sandstones contain about 55 percent feldspar and about 45 percent quartz. The Spencer Formation is assumed to be widespread under the younger rocks of the Willamette Valley and to be equivalent to the upper part of the Cowlitz Formation, or slightly younger than the Bateman and Coaledo Formations.

Coos Bay Basin

The Coos Bay Basin is located in the southwestern part of the Oregon Coast Range (figs. 24 and 25). The basin is a roughly elliptical structural basin measuring approximately 35 mi north–south and about 11 mi east–west (fig. 24). More than 12,000 ft of sedimentary rocks were deposited in the basin beginning in the early Eocene and ending in the Pleistocene (fig. 26).

The oldest rocks exposed in the coastal part of the Coos Bay Basin are in the middle Eocene Elkton Formation (figs. 8, 12, and 27), which crops out in the sea cliffs at Cape Arago (fig. 24). Overlying the Elkton Formation is more than 6,000 ft of coal-bearing rocks of the middle Eocene Coaledo Formation. The Coaledo Formation, which is present only in the complex structural Coos Bay Basin (fig. 25), was divided into three informal members by Allen and Baldwin (1944). The lower member of the Coaledo Formation (figs. 26, 28, and 29) consists of tuffaceous sandstone with minor conglomerate, pebbly sandstone, siltstone, carbonaceous mudstone, and coal deposited in a deltaic environment; thickness ranges from 1,700 to at least 1,900 ft (Allen and Baldwin, 1944; Baldwin and others, 1973; Armentrout, 1980). Excellent exposures of cross bedding, large load structures (flame structures), and sole markings can be seen at Sunset Bay (figs. 30 and 31). The middle member of the Coaledo Formation (figs. 26 and 32) is mostly thin-bedded siltstone with minor thin beds of sandstone and tuff deposited during a maximum transgression event and is at least 2,940 ft thick (Armentrout, 1980). The upper member of the Coaledo Formation (fig. 26) is characterized by regression and the return to a deltaic environment from deeper

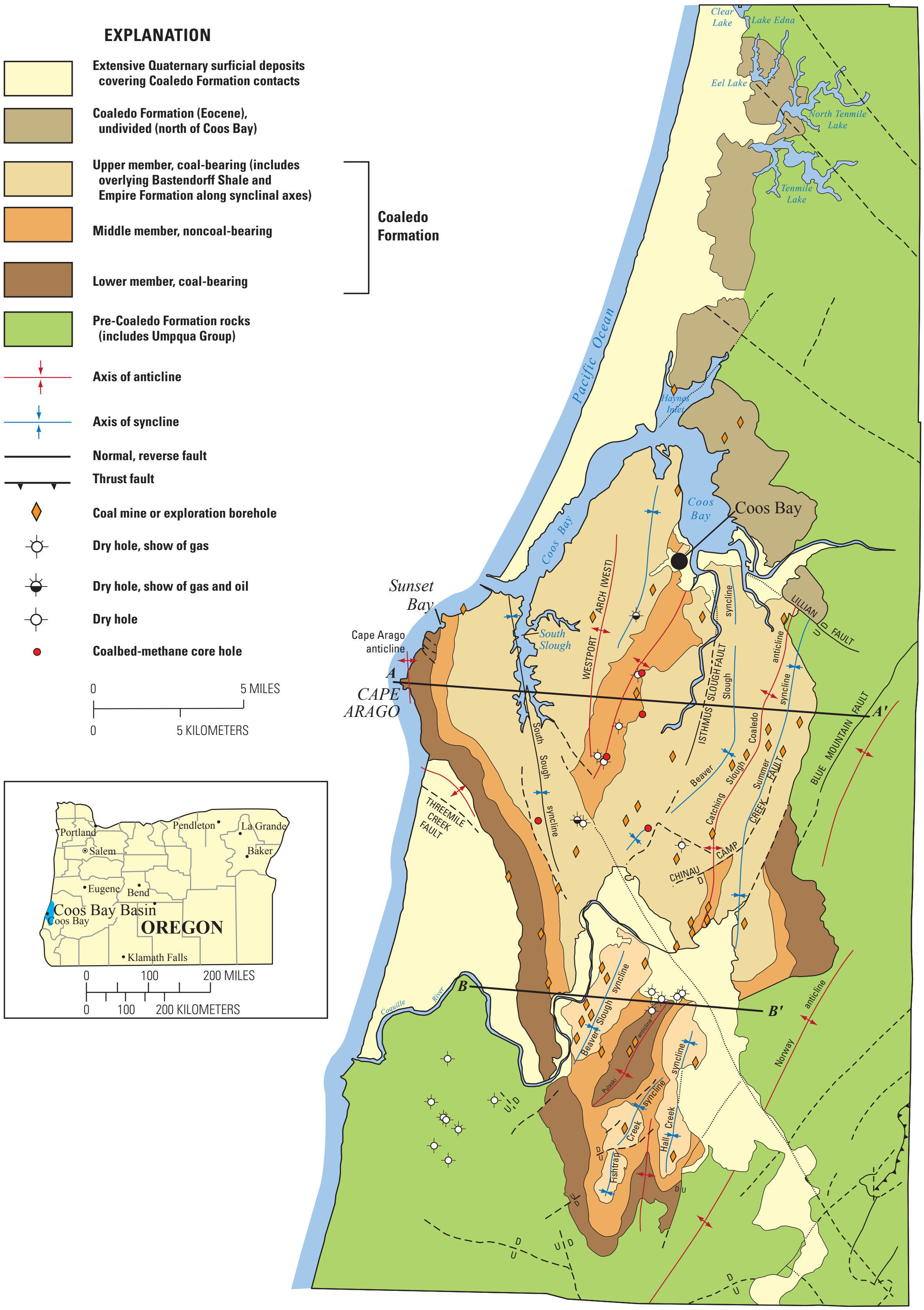

Figure 24. Generalized geologic map of the Coos Bay Basin and coal field. *A–A′* and *B–B′* are lines of cross section shown on figure 25. Modified after Baldwin and others (1973).

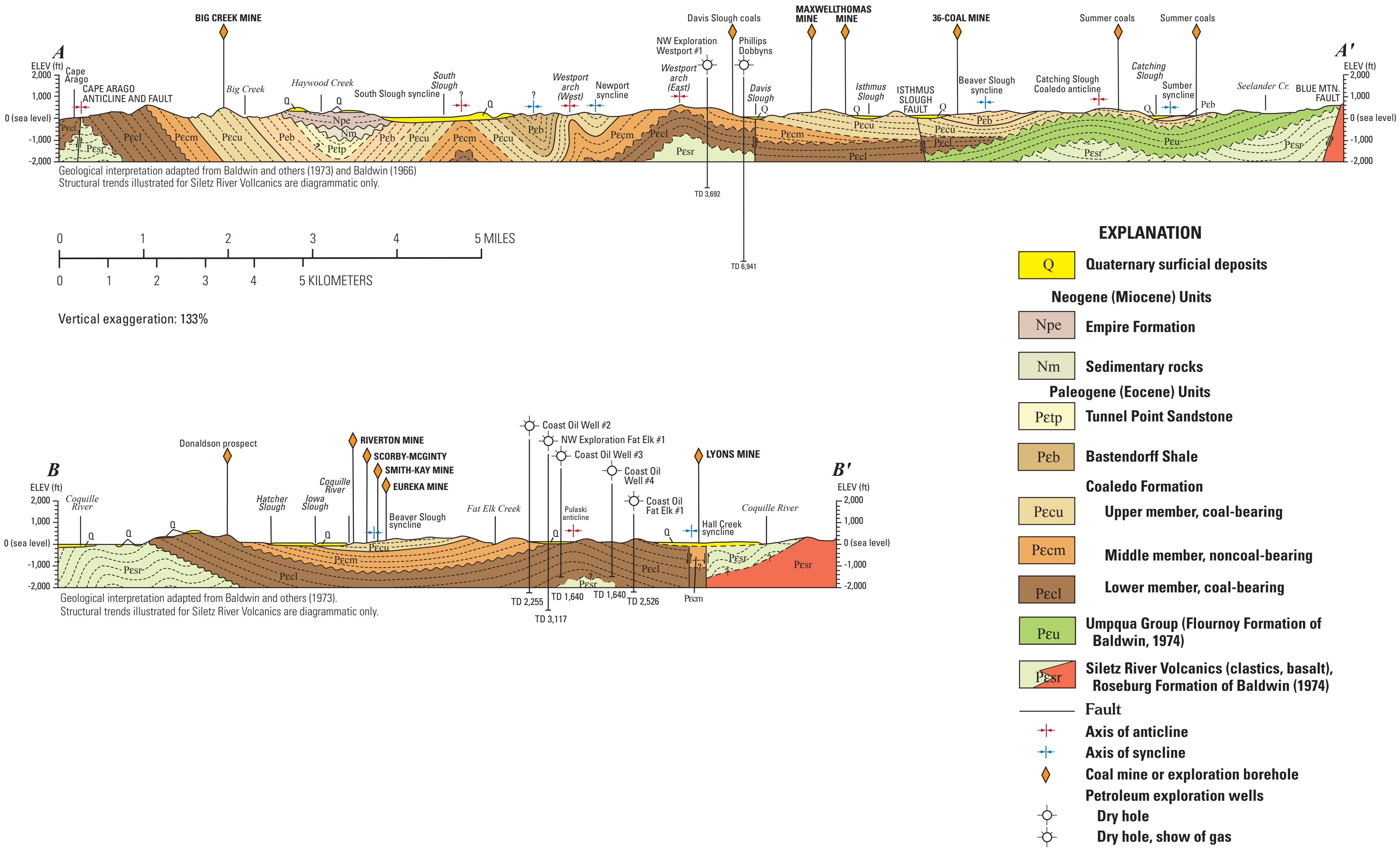

Figure 25. West to east cross sections across the Coos Bay Basin and coal field, Coos Bay Oregon. Location of cross section shown in figure 24. Modified after Baldwin and others (1973).

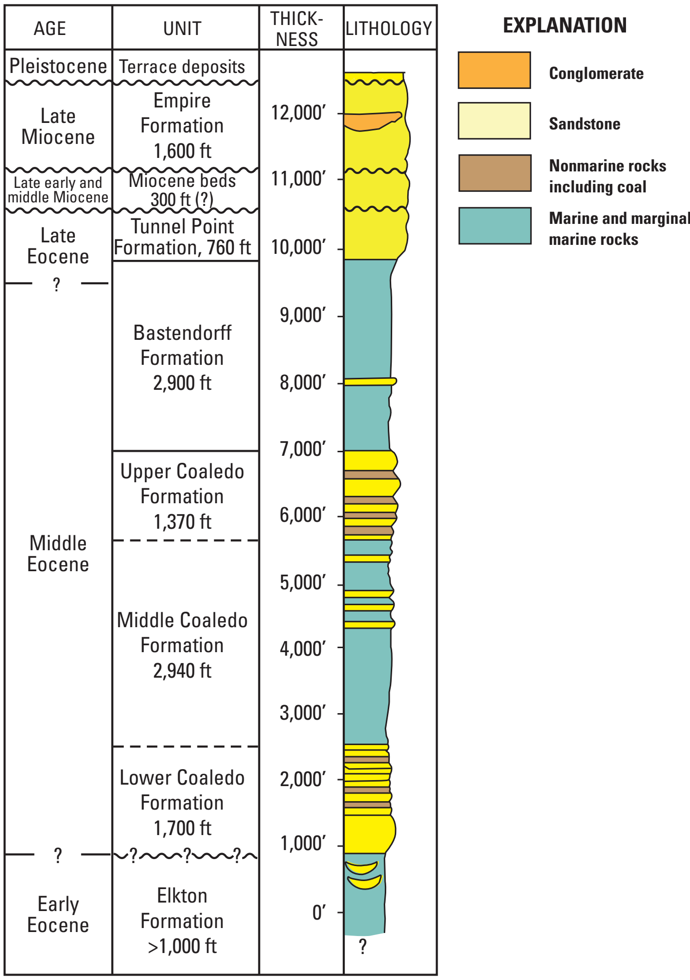

Figure 26. Stratigraphic section of Cenozoic rocks of the coastal part of the Coos Bay Basin, Coos Bay, Oregon. Modified after Armentrout (1980).

Figure 27. Outcrop of the middle Eocene Elkton Formation in the north cove of Cape Arago State Park, Oregon (see fig. 24).

Figure 28. Outcrop of the steeply dipping lower and middle members of the middle Eocene Coaledo Formation; view is north across Sunset Bay (see fig. 24). Middle member of the Coaledo is only exposed in the cliff on the far right of the photograph. The strata dip eastward toward the trough of the South Slough syncline in the Coos Bay coal field.

Figure 29. Outcrop of the steeply dipping lower member of the middle Eocene Coaledo Formation (see fig. 24), Shore Acres State Park, Oregon, north of Cape Arago (see fig. 24).

Figure 30. Outcrop of part of the middle Eocene lower member of the Coaledo Formation at Sunset Bay, near Coos Bay, Oregon (see fig. 24). Large load structures (flame structures) can be seen in the center of the photograph.

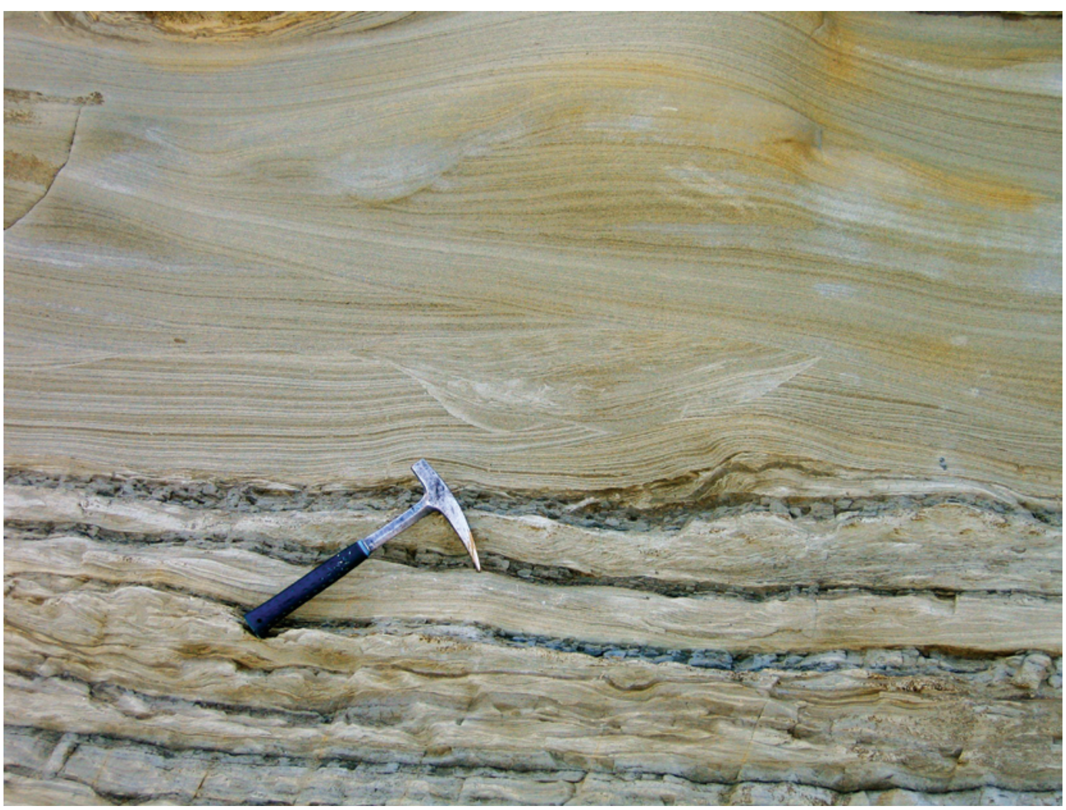

Figure 31. Outcrop of part of the middle Eocene lower member of the Coaledo Formation at Sunset Bay, near Coos Bay, Oregon (see fig. 24). Hummocky and swaley(?) cross-stratification can be seen in the center of the photograph.

Figure 32. Outcrop of the middle member of the middle Eocene Coaledo Formation, Sunset Bay, Oregon (see fig. 24).

marine environments and consists of tuffaceous sandstone with minor beds of siltstone, carbonaceous mudstone, and coal with thicknesses ranging from 2,300 to 2,900 ft (Baldwin and others, 1973; Armentrout, 1980).

Astoria Formation

Rocks assigned to the lower to middle Miocene Astoria Formation (figs. 5, 6, and 8) crop out in the northernmost part of the Oregon Coast Range along the lower Columbia River (figs. 1 and 2) and along the northern Oregon coast in a series of embayments from Newport to Astoria (fig. 6). The stratigraphic definition of the Astoria Formation varies in the different mapped areas in northwestern Oregon because the correlation with the type area has been on a faunal basis and not on the basis of lithology or continuous mapping into the type area.

The Astoria Formation was first described by Dana (1849) for exposures in Astoria, Oreg. Howe (1926) informally divided the Astoria into three members: (1) a lower unit, about 150 ft thick, consisting of yellow to gray, massive to cross-bedded, medium- to fine-grained, arkosic sandstone interbedded with mudstone; (2) a middle unit consisting of at least 1,000 ft of mudstone and interbedded thin glauconitic sandstone; and (3) an upper unit characterized by several massive to cross-bedded arkosic sandstone beds ranging in thickness from 10 to 100 ft. Most of the original exposures described by Howe (1926) are now obscured by man-made structures or by sand dredged from the Columbia River.

In the Newport area, about 100 mi south of Astoria (fig. 6), the stratigraphic relations of the Astoria Formation are more clearly defined (Vokes and others, 1949; Snavely and others, 1969). About 2,000 ft of Astoria Formation crops out in the Newport embayment, where it unconformably overlies the lower Miocene Nye Mudstone (fig. 33) and the upper Oligocene Yaquina Formation and is unconformably overlain by the middle Miocene basalt of Depoe Bay. The Astoria Formation consists mostly of shallow marine arkosic and micaceous sandstone (fig. 34) and carbonaceous siltstone.

The Astoria Formation in the northern part of the Oregon Coast Range has been divided into four informal members by Niem and Niem (1985): the deltaic to marginal marine Angora Peak, the shallow marine Wickiup Mountain, the submarine channel and fan Youngs Bay, and the turbidite Cannon Beach. The Angora Peak member (figs. 35–37), ranging in thickness from about 200 ft to more than 800 ft, consists of thick bedded

Figure 33. Outcrop of the lower Miocene Nye Mudstone (base of photograph) and the overlying unconformable middle Miocene Astoria Formation at Nye Beach, Newport, Oregon (see fig. 6).

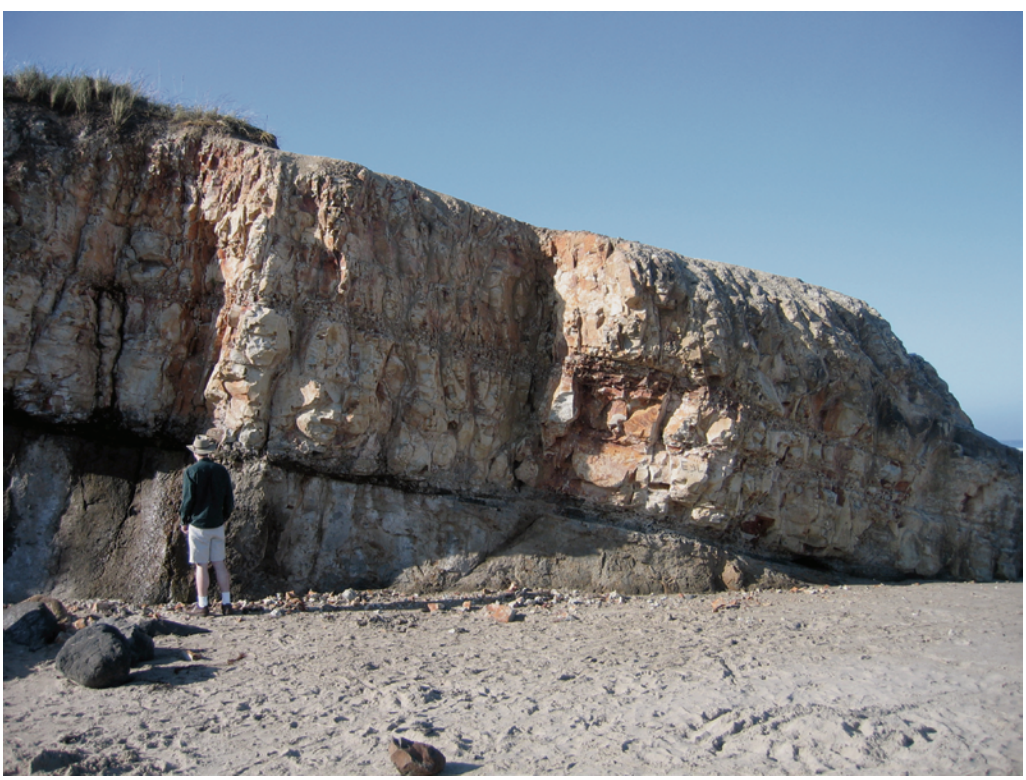

Figure 34. Outcrop of thick well-bedded arkosic sandstone of the middle Miocene Astoria Formation at Nye Beach, Newport, Oregon (see fig. 6)

Figure 35. Outcrop of the inclined strata of the informal Angora Peak member of the Astoria Formation overlain by a Quaternary terrace. Outcrop north of Otter Crest State Park, north of Newport, Oregon (see fig. 6).

Figure 36. Outcrop of the informal Angora Peak member of the Astoria Formation showing cross-stratification in conglomerate and sandstone beds along beach at Hug Point State Park north of Tillamook, Oregon (see fig. 6).

Figure 37. Close-up images of cross-stratification in the informal Angora Peak member of the Astoria Formation, northern Oregon Coast Range. *A*, Outcrop of the Angora Peak member showing planar and trough cross-stratification in conglomerate and sandstone beds along beach at Hug Point State Park north of Tillamook, Oregon (see fig. 6). *B*, Outcrop of the Angora Peak member showing detail of the cross-stratification in conglomerate and sandstone beds along beach at Hug Point State Park north of Tillamook, Oregon (see fig. 6). Note 3-in. knife for scale.

and laminated arkosic sandstone and lithic sandstone with minor conglomerate, mudstone, and thin coals. The Wickiup Mountain member is characterized by as much as 1,300 ft of structureless to laminated shallow-water arkosic sandstone and minor mudstone capped by glauconitic sandstone. The Youngs Bay member is mostly deep-marine mudstone as much as 2,200 ft thick, interbedded with two lenticular, medium- to coarse-grained arkosic sandstone units, 200 and 1,000 ft thick, respectively. The Cannon Beach member ranges in thickness from about 2,000 ft in the Tillamook area (Wells and others, 1994) to several thousand feet near Astoria (fig. 6) (Niem and Niem, 1985), and consists of well-bedded siltstone and mudstone with minor amounts of rhythmically bedded, graded arkosic sandstone.

Western Washington

The western Washington part of the Western Oregon and Washington Province (figs. 3 and 4) occupies a complex geologic setting along the northwestern continental margin of North America and is bounded on the north by the International Boundary in the Straits of Juan de Fuca and San Juan Islands (fig. 3). It extends offshore to the 3-mi limit of State waters on the west and on the east by the approximate crest of the Cascade Range. The region overlies a major north-trending crustal boundary between basement rocks of the pre-Tertiary Northern Cascade Range and Cascade arc to the east and the Eocene Coast Range to the west (figs. 2, 4, and 38). The Puget fault, also known as the Coast Range boundary fault (Johnson and others, 1996), is mostly buried by Quaternary deposits in the Puget Lowland (fig. 38; also see fig. 41).

Pre-Tertiary

Pre-Tertiary basement rocks of the Northern Cascades include diverse metamorphic, igneous, and sedimentary rocks that form several distinct crustal terranes with allochthonous and (or) exotic origins (figs. 4, 7, and 38). The final stages of accretion of these crustal terranes were completed by the Late Cretaceous, after which these rocks formed the stable platform of the Washington continental margin. During the early to early middle Eocene, the eastern pre-Tertiary basement underwent significant dextral strike-slip faulting and transtensional deformation. This deformation was manifested by the formation of rapidly subsiding sedimentary basins with common intrabasinal volcanic centers and uplift and (or) igneous intrusion of the crystalline rocks (Johnson, 1985). Eocene sedimentary rocks within these basins are as thick as 20,000 ft and constitute some of the thickest nonmarine successions in North America (Johnson, 1985).

Crescent Formation

The basement rocks of the Washington Coast Range consist of lower and lower middle Eocene marine basalts and volcaniclastic rocks of the Crescent Formation, which was named for Port Crescent on the south shore of Strait of Juan de Fuca, west of Port Angeles, Wash. (figs. 4, 5, 7, and 38). The Crescent Formation (fig. 39) consists of massive pillow and diabasic basalt flows, flow- and tuff-breccia, and tuff with interbedded basaltic conglomerate and sandstone, and well-indurated, massive tuffaceous siltstone, argillite, and minor limestone (Brown and others, 1960; Cady and others, 1972; Wolfe and McKee, 1968, 1972; Whetten and others, 1988). In the Tofino-Fuca Basin (fig. 5), the Crescent Formation underlies and interfingers with the Aldwell Formation (see fig. 47). The Crescent Formation is in part equivalent to the Siletz River Volcanics of Oregon and may be as much as 25,000 ft thick (Rau, 1964). These rocks are now widely believed to have formed in a continental-margin rift setting (Wells and others, 1984; Snavely, 1987; Babcock and others, 1992).

Post-rift subsidence of the Washington Coast Range is thought to be of thermal origin (Johnson and Yount, 1992). Johnson (1984c, 1985) and Johnson and others (1994, 1996) suggested that the eastern margin of this rifted terrain is coincident with the dextral strike-slip Puget fault (fig. 38). Northward motion of the Coast Range block along the Puget fault was accommodated to the north by south-directed thrusting on southern Vancouver Island (Clowes and others, 1987), and folding and faulting within the Coast Range block in the Straits of Juan de Fuca and on the northern Olympic Peninsula (Snavely, 1987). Johnson (1984c, 1985) suggested that most strike-slip motion on the crustal boundary occurred prior to the late Eocene, after which strike-slip motion diminished and was distributed on several fault zones in the southeastern Puget Lowland (Johnson and others, 1994). The Puget fault is covered by upper Eocene and higher strata and is located and delineated mainly with geophysical data.

Bellingham Basin

The Eocene Chuckanut Formation (Johnson, 1982; Johnson, 1984a) of the Bellingham Basin area of northwest Washington consists of alluvial strata as much as 19,690 ft thick, one of the thickest nonmarine sequences in North America (figs. 5, 38, and 40). The Chuckanut is present in several structurally low outcrop belts, located west of Mount Baker in the Northern Cascades. These outcrop belts are remnants of a much larger Eocene fluvial system in western Washington. The Eocene of western Washington overlies a complex pre-Tertiary basement that is cut by thrust faults of mid-Cretaceous age and strike-slip faults of Late Cretaceous to early Eocene age (Whetten and others, 1988). The Chuckanut Formation unconformably overlies the pre-Tertiary rocks along the northern and southern contacts and is bounded by high-angle faults to the east (Misch, 1977; Tabor and others, 2003). The Chuckanut Formation was subdivided into seven members by Johnson (1984a), which are, in ascending order, the Bellingham Bay, Governors Point, Padden, Slide, Maple Falls, Warnick, and Bald Mountain Members. These units range in age from early to late Eocene. South of the main Chuckanut outcrop belt, the

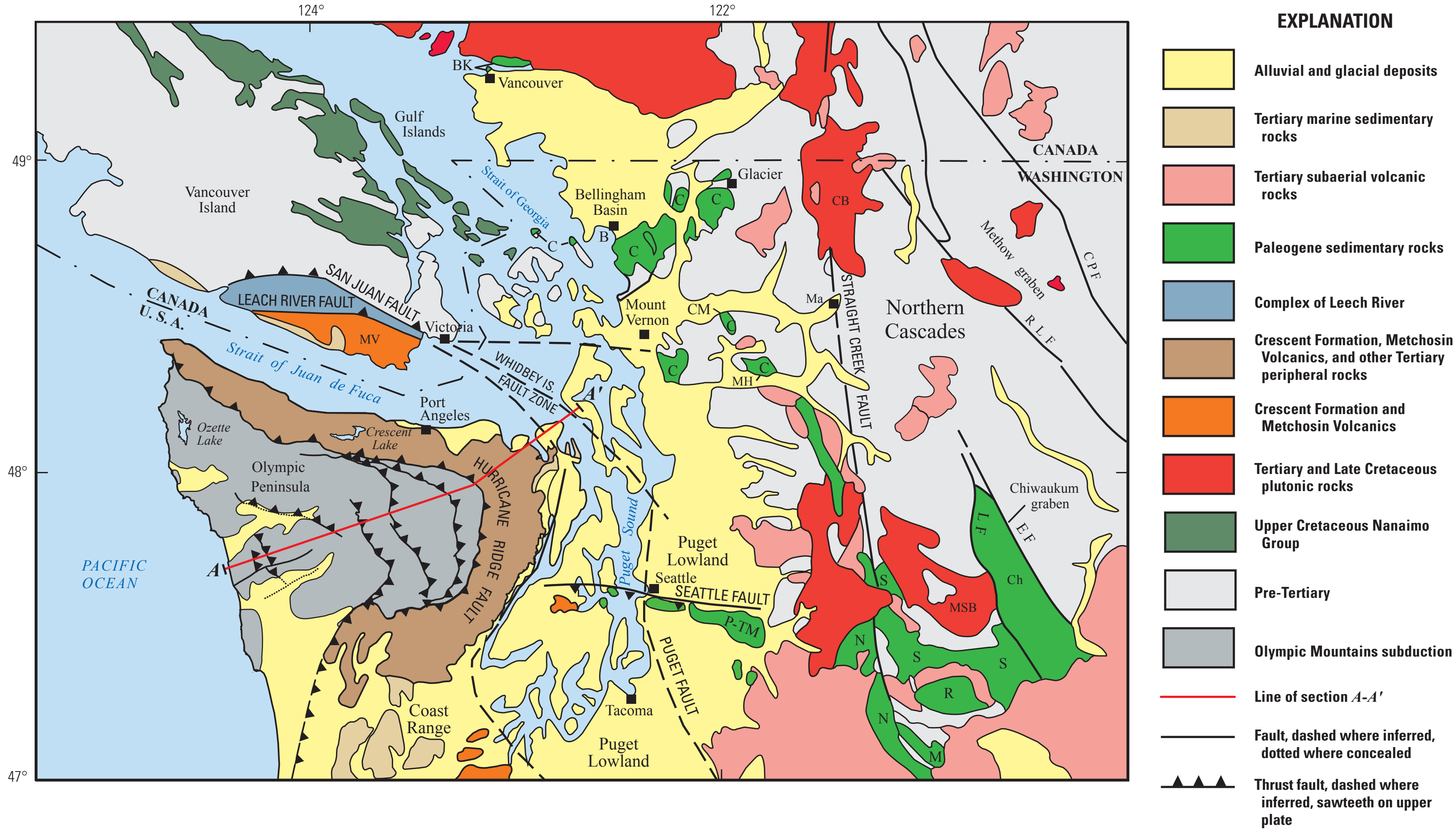

Figure 38. Generalized geologic map of northwestern Washington and southwestern British Columbia, Canada. Cross section *A-A′* shown in figure 50. B, Bellingham; BK, Burrard and Kitsilano Formations; C, Chuckanut Formation ;CB, Chilliwack batholith; CM, Coal Mountain; CPF, Chewack-Pasayten fault; Ch, Chumstick Formation; EF, Enitat fault; LF, Leavenworth fault; M, Manastash Formation; MH, Mount Higgins; MSB, Mount Stuart batholith; Ma, Marblemount; N, Naches Formation; P-TM, Puget Group and Tiger Mountain area (location of Raging River Formation); R, Roslyn Formation; RLF, Ross Lake fault; S, Swauk Formation. Modified after Johnson (1984a), Snavely and Wells (1991), Snavely, MacLeod, and Niem (1993), and Mustard (1994).

Figure 39. Outcrops of the lower to middle Eocene Crescent Formation. *A*, Exposure of basalt pillows and volcaniclastic rocks in road cut along Hurricane Ridge Road, Olympic National Park, Washington. *B*, Exposure of basalt pillows of the Crescent Formation in Salt Creek Park, Washington Route 112, Olympic Peninsula, Washington.

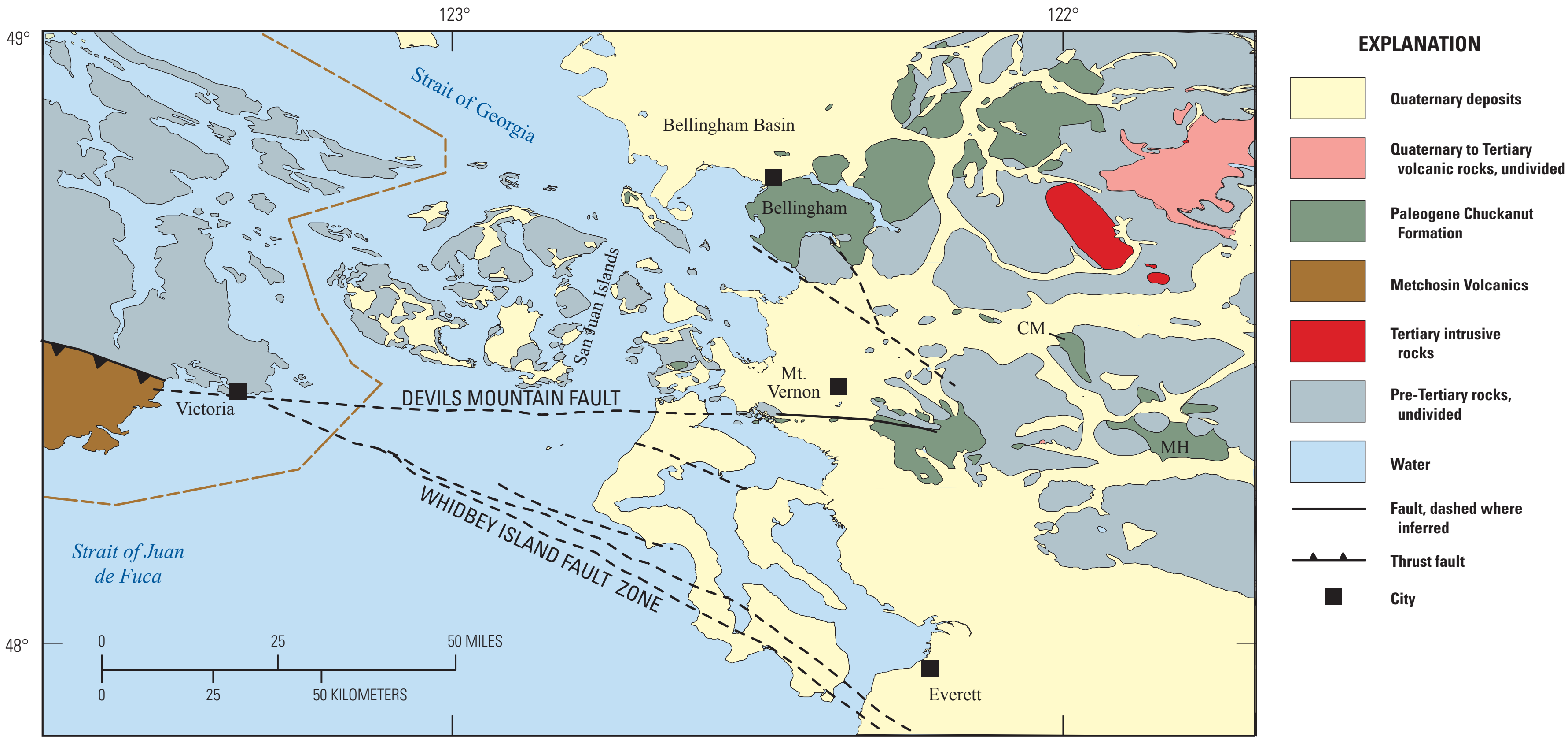

Figure 40. Generalized geologic map of the Bellingham area, northwestern Washington, and Vancouver Island, Canada, showing rock units and major faults. CM, Coal Mountain; MH, Mount Higgins. Modified after Schuster (2005).

rocks are assigned to the undivided Chuckanut at Coal Mountain, Mount Higgins, and in localities southeast of the town of Mount Vernon (figs. 38, 40).

Early Tertiary time in the Bellingham Basin was dominated by rapid uplift of pre-Tertiary rocks to the east, active strike-slip faulting, volcanic activity, and alluvial sedimentation in rapidly subsiding basins. The Bellingham Bay Member represents early Eocene deposition of the Chuckanut Formation and was interpreted by Johnson (1984a,b) as representing meandering-river and adjacent flood-plain deposits in a rapidly subsiding basin, with a distant source area to the east. Early reports by Woodruff (1914), Jenkins (1923, 1924), and Moen (1969) discussed the geology and coal deposits in this region. More recent investigations concerning the coal deposits have been published by Beikman and others (1961), Vonheeder (1975, 1977), and Brownfield and others (1995).

The Bellingham Bay Member of the Chuckanut Formation consists of nonmarine sandstone, mudstone, carbonaceous shale, and coal grouped into alternating coarse-grained and fine-grained sequences that represent fining-upward cycles (Johnson, 1984a); coals are near the base of the member. The Bellingham Bay Member is 8,860 ft thick in the western part of the outcrop belt and 10,830 ft thick in the eastern part of the outcrop belt, south of Glacier, Wash. (fig. 38).

Puget Lowland

The northern part of the Puget Lowland (or Seattle Basin), located southwest of the Northern Cascades (figs. 2 and 38), is generally underlain by the basalts and volcaniclastic marine rocks of the lower to middle Eocene Crescent Formation (figs. 5, 7, and 39). In the late Paleogene, tectonism partitioned western Washington into smaller basins and uplifts (Wells and Coe, 1985), and sediments were deposited in fluvial, deltaic, and marginal marine environments over the basement volcanic rocks.

The lower(?) to middle Eocene Raging River Formation (fig. 5), named by Vine (1962), is the oldest sedimentary unit that outcrops in the eastern part of the central Puget Lowland in the Tiger Mountain area (figs. 38 and 41). Its base is not exposed in the area, but the exposed part ranges in thickness from about 2,000 ft to more than 3,000 ft (Vine, 1962; Vine, 1969; Johnson and O'Connor, 1994). The Raging River Formation consists of fine-grained sandstone, siltstone, and claystone. Johnson and O'Connor (1994) divided the Raging River into three informal units in the Tiger Mountain area. The lower unit is about 755 ft thick and consists of interbedded sandstone, mudstone, and conglomerate; the lower part of the lower unit is nonmarine, and the upper part is shallow marine in origin. The middle unit, about 610 ft thick, is mainly nonmarine interbedded conglomerate, sandstone, and mudstone. The upper unit consists of about 980 ft of gray, silty, organic-rich mudstone and minor sandstone that was deposited along the marine shelf and bathyal slope and may also be present at depth to the west beneath Puget Sound.

The middle Eocene Tiger Mountain Formation of the Puget Group (fig. 5) overlies the Raging River Formation in the Tiger Mountain area (Vine, 1962; Vine, 1969; Johnson and O'Connor, 1994). The Tiger Mountain Formation is about 2,000 ft thick and consists mainly of arkosic sandstone, siltstone, carbonaceous shale, and minor coal; the upper part of the unit interfingers with the middle to upper Eocene Tukwila Formation of the Puget Group (fig. 5). The Tukwila Formation consists mostly of volcanic and volcaniclastic rocks (Vine, 1962; Vine, 1969; Johnson and O'Connor, 1994), ranges in thickness from 2,460 ft to as much as 6,800 ft in the Tiger Mountain area (figs. 38 and 41), and possibly interfingers with the overlying middle to upper Eocene Renton Formation also of the Puget Group. The Renton Formation, 2,250 ft to more that 3,400 ft thick (Vine, 1962; Vine, 1969; Johnson and O'Connor, 1994), consists mainly of fine- to medium-grained arkosic sandstone with lesser amounts of siltstone; it also consists of carbonaceous shale as well as minor coal.

Upper middle Eocene and upper Eocene coal-bearing strata in the central and northern parts of the Puget Lowland (Beikman and others, 1961) are assigned to the undivided Puget Group (fig. 5) (Vine, 1969). Vine (1969) compiled a composite 5,250-ft-thick stratigraphic section based on surface and shallow subsurface data in the Green River district southeast of Seattle (fig. 2). The Green River district is structurally complex with numerous faults and tight folds with bedding-plane attitudes ranging from gentle to overturned. At the John Henry No. 1 mine, coal was mined along the flanks of a tightly folded anticline that illustrates this structural style (fig. 42) (Brownfield and others, 1994; Brownfield and others, 2005).

Sedimentological analysis of the undivided Puget Group in the Green River district is limited due to the distribution and poor quality of the exposures. The following preliminary interpretation is based mainly on the 6,300-ft measured section by Vine (1969) exposed in the canyon of the Green River and at the John Henry No. 1 mine near Black Diamond, Wash. (fig. 42) (Brownfield and others, 1994; Brownfield and others, 2005). Rocks in the Green River section of the Puget Group dip gently to steeply exposing most of the coal-bearing stratigraphic interval; however, there is virtually no control on the lateral distribution of facies, because of the extensive forest cover. The Puget Group section consists of alternating sequences of coarse-grained sandstone and fine-grained deposits of mudstone, very fine to fine-grained sandstone, and coal having characteristics of both deltaic and fluvial environments (Brownfield and others, 1994). The delta was fluvial-dominated, but influenced by tides and to a lesser extent by waves. The fluvial deposits include both channel and interchannel strata.

Puget Group strata of fluvial origin within the Green River canyon and in the vicinity of, and within, the John Henry mine form sandstone bodies ranging in thickness from about 20 to 158 ft (Brownfield and others, 1994; Brownfield and others, 2005). These bodies consist mainly of fine- and medium-grained sandstone; coarse-grained sandstone is uncommon, and conglomerate is rare. Channels typically

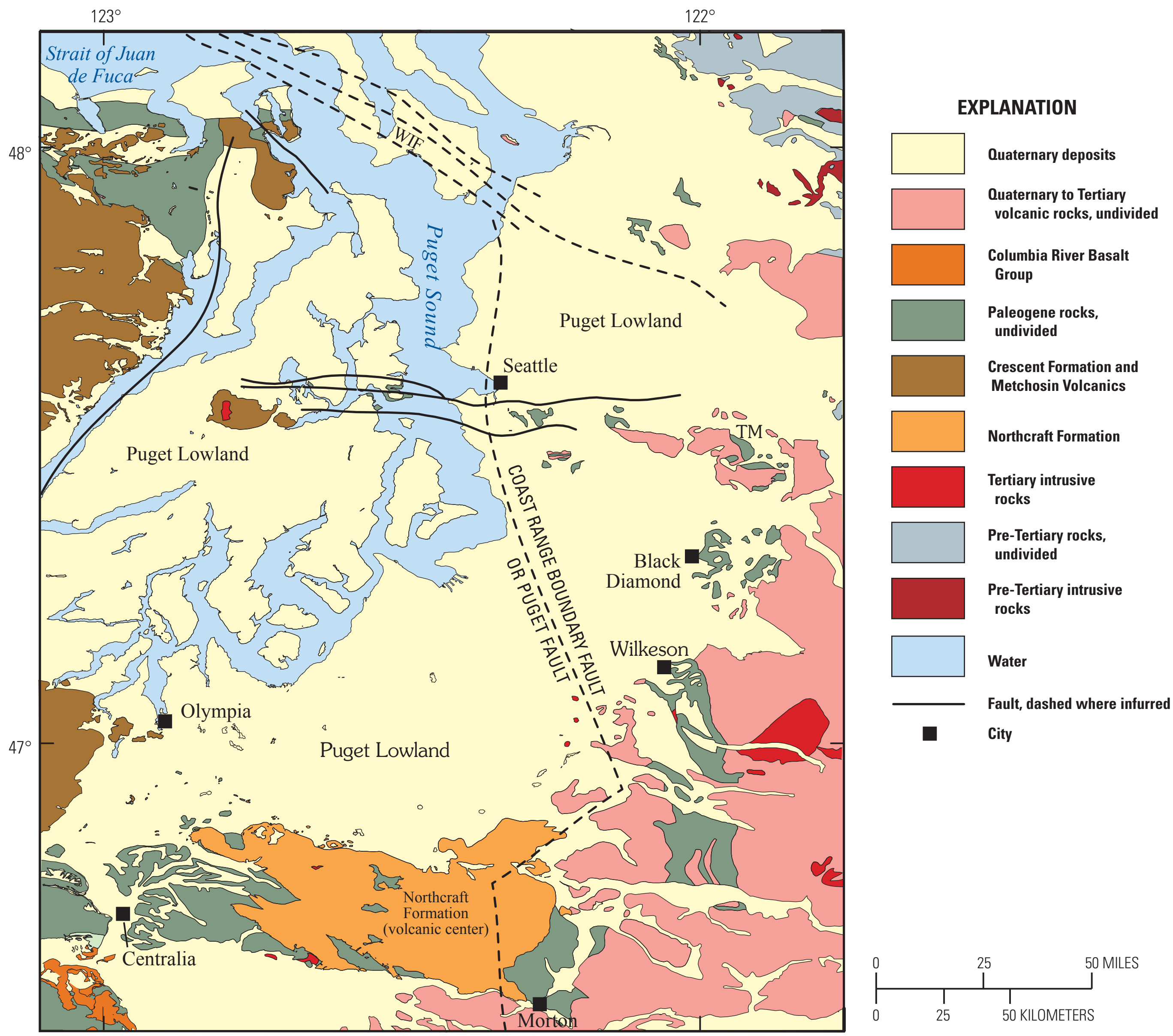

Figure 41. Generalized geologic map of the Puget Lowland area, northwestern Washington, showing geologic units and major faults. TM, Tiger Mountain; WIF, Whidbey Island fault. Modified after Schuster (2005).

Figure 42. Outcrops of the Puget Group at the Pacific Coast Coal Company's John Henry No. 1 mine near Black Diamond, Washington (see fig. 41). The strata dip steeply over a doubly plunging anticline on the left side of the photograph.

Figure 43. Outcrop of the Franklin No. 10A coal bed in John Henry No. 1 mine near Black Diamond, Washington (see fig. 41). Rocks above coal consist of fine-grained overbank deposits, cut into by a thick channel sandstone, which is overlain by a fine-grained floodbasin facies.

have sharp, erosional lower contacts (fig. 43), and many sandstone bodies include internal low-angle, trough-shaped scour surfaces that can be traced laterally for as much as 50 ft. Both basal and internal scour surfaces are commonly overlain by lags of wood fragments (with rare *Teredo* borings) and rip-up clasts. The sandstone is trough crossbedded, planar to low-angle bedded, and ripple laminated. Thick (13–33 ft) sets of low-angle (10°–20°) dipping strata, interpreted as lateral accretion surfaces on point bars, are present in several sandstone bodies. Fine-grained mudstone drapes, in many cases burrowed, are present on bedding planes within point-bar deposits. A fluvial channel origin for these sandstone bodies is inferred based on texture and internal sedimentary structures, as outlined above. Location of these channels on a delta plain is supported by the presence of burrowed mudstone drapes on point-bar deposits (Thomas and others, 1987; Shanley and others, 1992), *Teredo*-bored wood, and the sedimentology of bounding fine-grained strata.

Puget Group strata that are interpreted as interchannel deposits (including levee, flood-plain, shallow-lake, crevasse-channel, crevasse-splay, and peat-swamp environments) consist of mudstone and fine-grained sandstone, and less common carbonaceous shale and coal (Brownfield and others, 1994; Brownfield and others, 2005). These fine-grained units are 3 to more than 65 ft thick. Parallel and (or) ripple lamination is common; however, in many cases primary sedimentary structures have been partly or wholly destroyed by burrows, root traces, and pedogenesis. Fossil plant material is common in these beds (Wolfe, 1968; Burnham, 1990). Within the thicker fine-grained intervals, two types of deposits are recognized: (1) lenticular beds of ripple-laminated, horizontal-bedded, and trough-crossbedded, very fine to fine-grained sandstone generally less than 3 ft thick interpreted as crevasse-channel deposits; and (2) sheet-like beds of ripple-laminated and horizontal-bedded, very fine to fine-grained sandstone generally less than 1.5 ft thick inferred to be crevasse-splay deposits.

Beds of coal, carbonaceous shale, and minor mudstone representing peat-swamp deposition are also present in the Puget Group, ranging in thickness from a few inches to as much as 40 ft. Altered tuff beds or tonstein partings are common in the stratigraphically lower coal, indicating moderate Paleogene volcanism during the time of peat accumulation. Tonsteins are rare to absent in stratigraphically higher coal beds. The clastic section above the Franklin No. 10A coal bed in the John Henry No. 1 mine consists of fine-grained overbank deposits that are cut into by a large channel sandstone, which is overlain in turn by more fine-grained floodbasin facies (fig. 43). Vertical tree trunks and petrified wood are present in several coal beds. Burnham (1990) suggested that coals of the Puget Group formed in raised mires; however, the abundance of mudstone partings and tonsteins in many coals suggests that peat swamps also occupied low-lying parts of the delta plain.

Strata of inferred brackish to shallow-marine origin consist of stratified to massive sandstone and mudstone. Stratification includes parallel and ripple lamination, wavy, flaser, and lenticular bedding, and relatively small-scale trough crossbedding (set thickness ≤1 ft). Crossbed sets are bidirectional (dipping up and down the regional paleoslope) and contain common mudstone drapes. Mudstone drapes and thin (<0.2 in.) carbonaceous laminations are common. This suite of sedimentary structures indicates fluctuating depositional energy and probable tidal influence (Shanley and others, 1992). Hummocky crossbedding and wave-ripple lamination are rare but indicate minor wave influence. Primary stratification has been partly to completely destroyed in many sandstone and mudstone beds of inferred brackish to shallow-marine origin by intensive bioturbation. Burrowing animals led to differential cementation in many beds, resulting commonly in an irregular and knotty weathering profile. Plant fragments, including *Teredo*-bored wood, are common in massive sandstone beds; shell fragments (pelecypod and gastropod) are present in a few beds. Evidence for both tidal, and to a lesser degree, wave influence, indicates deposition in a variety of delta-plain and delta-front environments, including bays, estuaries, mouth bars, and shorefaces.

Coal-bearing rocks in the Wilkeson-Carbonado area (figs. 2 and 41) are in the middle Eocene Carbonado Formation of the Puget Group (fig. 5) and consist of interbedded sandstone, siltstone, mudstone, carbonaceous shale, and coal more than 5,000 ft thick (Gard, 1968). The basal contact of the Carbonado Formation is not exposed and in places is overlain by the Northcraft Formation of Puget Group. Where the Northcraft Formation is absent, the Carbonado is indistinguishable from Spiketon Formation of Puget Group (fig. 5).

North of Morton, Wash. (fig. 41), the Carbonado Formation (fig. 5) is about 3,900 ft thick (Johnson and Stanley, 1995) and consists of nonmarine and shallow- to marginal-marine rocks deposited in fluvial and tidally influenced delta environments. The marine rocks are shoreface sandstone and laminated sandstone and mudstone, and the nonmarine rocks include sandstone, mudstone, coal, and carbonaceous mudstone.

Southern Puget Lowland

The oldest rocks exposed in the southern Puget Lowland area (figs. 5 and 44) are the lower Eocene Crescent Formation, which is unconformably overlain by the middle to upper Eocene McIntosh Formation (fig. 5). The McIntosh Formation consists of dark-gray marine siltstone and mudstone and interbedded arkosic and basaltic sandstone ranging in thickness from 4,000 to 4,500 ft (Snavely and others, 1951, 1958). Overlying the McIntosh is the coal- and carbonaceous-shale-bearing Skookumchuck and Cowlitz Formations (fig. 5).

The upper middle to upper Eocene Skookumchuck Formation (fig. 5) crops out in the Centralia-Chehalis district (fig. 2), where the stratigraphy and coal geology was described in detail by Snavely and others (1958). The Skookumchuck is about 3,825 ft thick in the district and consists of marginal-marine and shallow-marine rocks. Although present only in the Centralia-Chehalis district, the formation can be correlated

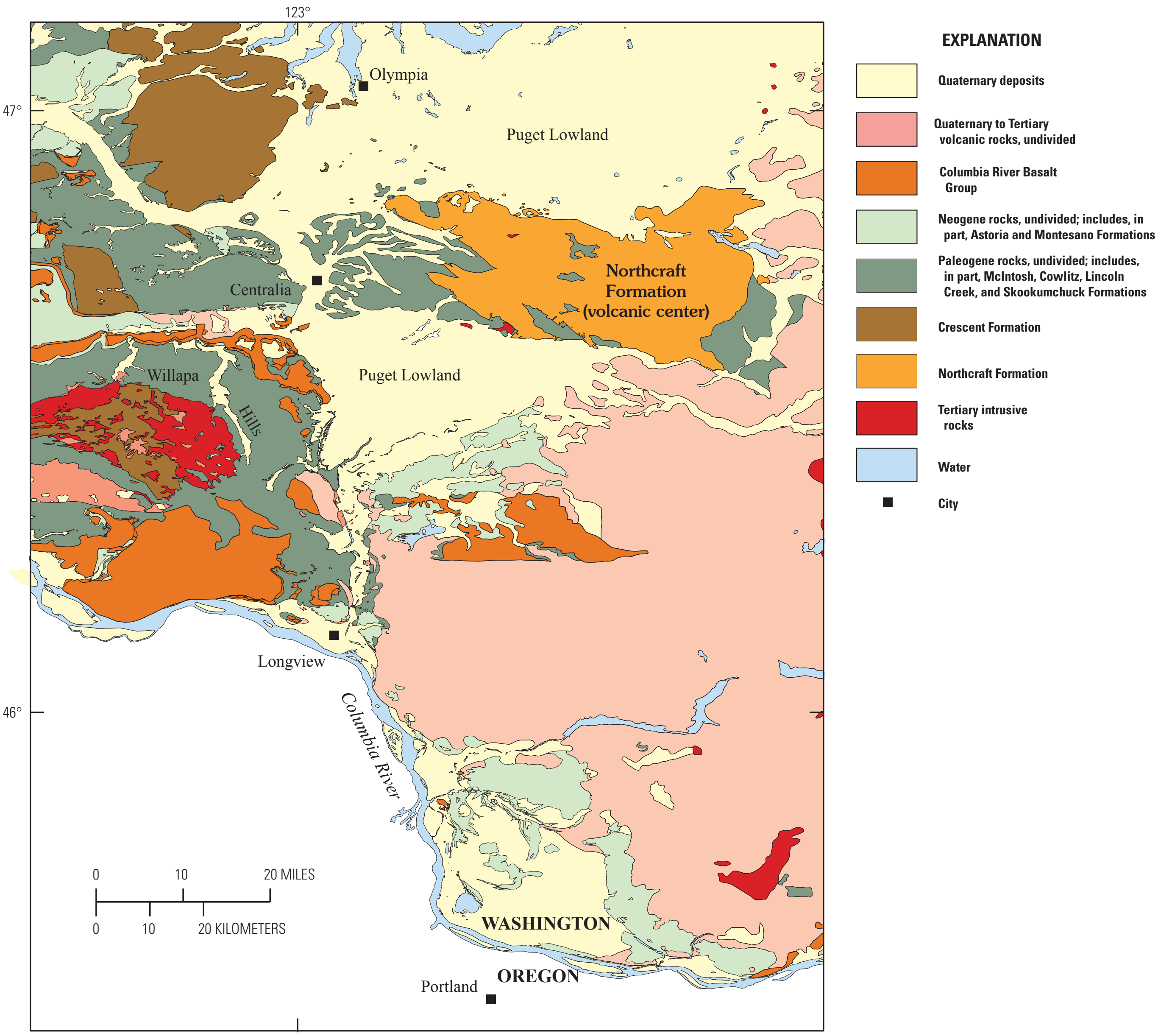

Figure 44. Generalized geologic map showing the southern part of the Puget Lowland and the Centralia coal area, southwestern Washington. Modified after Schuster (2005).

to other coal-bearing time-stratigraphic units to the north and south (fig. 3). The Skookumchuck Formation overlies and interfingers with the Northcraft Formation and is overlain by the Oligocene Lincoln Creek Formation (fig. 5).

Sedimentological evidence of detrital rocks in the Skookumchuck Formation in the Centralia mine (figs. 44 and 45) indicates that these deposits formed in a tidal-influenced coastal plain (Stevenson and Emery, 1958; Evans, 1965; Reineck and Singh, 1980). Within this setting, fine-grained rocks were deposited in tidal flats and coarser grained rocks (for example, sandstones) were deposited in tidal channels and bars. Lenticular, wavy, and flaser bedding; bidirectional ripple lamination; and mudstone drapes indicate fluctuating depositional energy and reversals of current direction. Abundant fossils, fossil fragments, and trace fossils indicate widespread biologic activity. Zones of root structures in these inferred intertidal deposits indicate periodic exposure in supratidal environments.

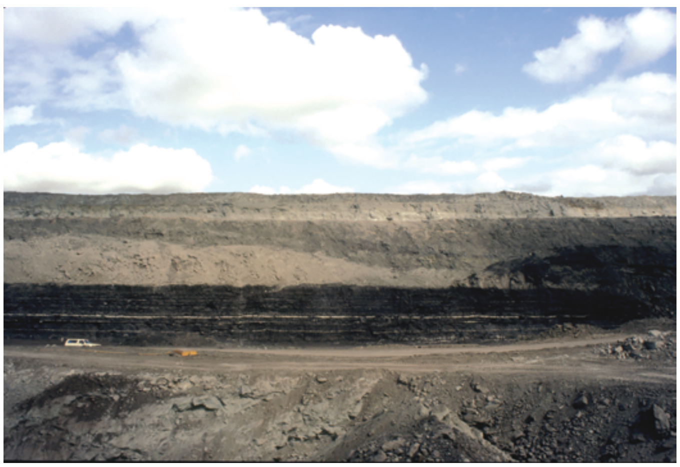

Figure 45. Outcrop showing the Big Dirty coal bed of the Skookumchuck Formation, in the Hanaford pit, at the Centralia mine, west of Centralia, Washington (see fig. 44). The coal bed is as much as 40 ft thick. White band is a volcanic ash parting.

Tidal-channel deposits are observed in a variety of scales. Larger channels are represented by units of scour-based, trough-crossbedded sandstone and include *Teredo*-bored wood fragments. A large channel deposit traverses the Big Dirty coal bed in the North Hanaford pit of the Centralia mine, east of Centralia, Wash. (fig. 44), indicating channel incision into a supratidal mire (Brownfield and others, 1994). Deposits of smaller tidal channels include relatively thin sets of tabular-crossbedded, silty to fine-grained sandstone units with reactivation surfaces that are interpreted as tidal bar deposits (Boersma and Terwindt, 1981).

The coal beds represent peat accumulation in supratidal mires that formed above mean high-tide level. The presence of abundant mudstone and of both airfall and water-laid volcanic-ash partings (fig. 45) suggests that these mires were low lying or topogenous. Clastic material would be unable to flow into raised mires, and volcanic ash would have been washed and dispersed into the peat by rainfall (Rupert and others, 1993; Rupert and Moore, 1993).

The middle to upper Eocene Cowlitz Formation, which crops out southwest of Centralia and northwest of Longview in the Willapa Hills (fig. 44), was deposited in marine, brackish-water, and nonmarine environments. At the type locality along the Cowlitz River, north of Longview, Wash. (fig. 44), the Cowlitz Formation is about 4,200 ft thick and is predominantly siltstone with massive arkosic sandstone, locally well developed, and sandy siltstone with minor amounts of coal and carbonaceous shale (Weaver, 1937; Roberts, 1958). The sandstone beds are mostly arkosic and are as much as 90 ft thick. Regionally, the Cowlitz Formation is as much as 9,500 ft thick and equivalent to the Skookumchuck Formation and in part to the McIntosh Formation (fig. 5) (Armentrout and others, 1980).

The Oligocene Lincoln Creek Formation (fig. 5) crops out west and east of Centralia, Wash. (fig. 44) (Snavely and others, 1958); it underlies much of the area east of Grays Harbor and Willapa Bay (fig. 7) and conformably overlies the Skookumchuck Formation. The Lincoln Creek Formation, where it crops out east of Centralia, consists of nearshore and continental units. These units grade laterally into marine tuffaceous siltstone and fine-grained sandstone that are about 1,500 ft thick near Centralia (fig. 44). The Lincoln Creek Formation thickens westward to as much as 9,000 ft thick southeast of Grays Harbor (fig. 7, also see fig. 54), where the Lincoln Creek Formation is predominantly marine tuffaceous siltstone and fine-grained tuffaceous sandstone (Armentrout and others, 1980).

The lower to middle Miocene Astoria Formation unconformably overlies the Lincoln Creek Formation in the southern Puget Lowland, where late Oligocene structural highs had developed. Because of these unconformable relations, the thickness of the Astoria Formation is variable, measuring only about 700 ft in the southern Puget Lowland area but increases to nearly 3,500 ft just east of Grays Harbor (fig. 8; also see fig. 54) (Rau, 1967). In the Centralia, Wash., area (fig. 44), the Astoria Formation consists generally of dark, medium-grained and carbonaceous fine-grained sandstone and locally glauconitic sandstone beds at its base (Armentrout and others, 1980). East of Centralia, the Astoria Formation contains basaltic conglomerate (Snavely and others, 1958).

Olympic Peninsula Area

The Tofino-Juan de Fuca Basin is located on the northern Olympic Peninsula of Washington (fig. 46) and occupies the Strait of Juan de Fuca (fig. 46). The Canadian term for this basin is the Tofino Basin (Shouldice, 1971), and Snavely and others (1980) referred to the basin as the Tofino-Fuca Basin. The Tofino-Juan de Fuca Basin is bounded on the north by Vancouver Island and to the south by the Olympic Mountains. Subsidence began in the middle Eocene resulting from thermal

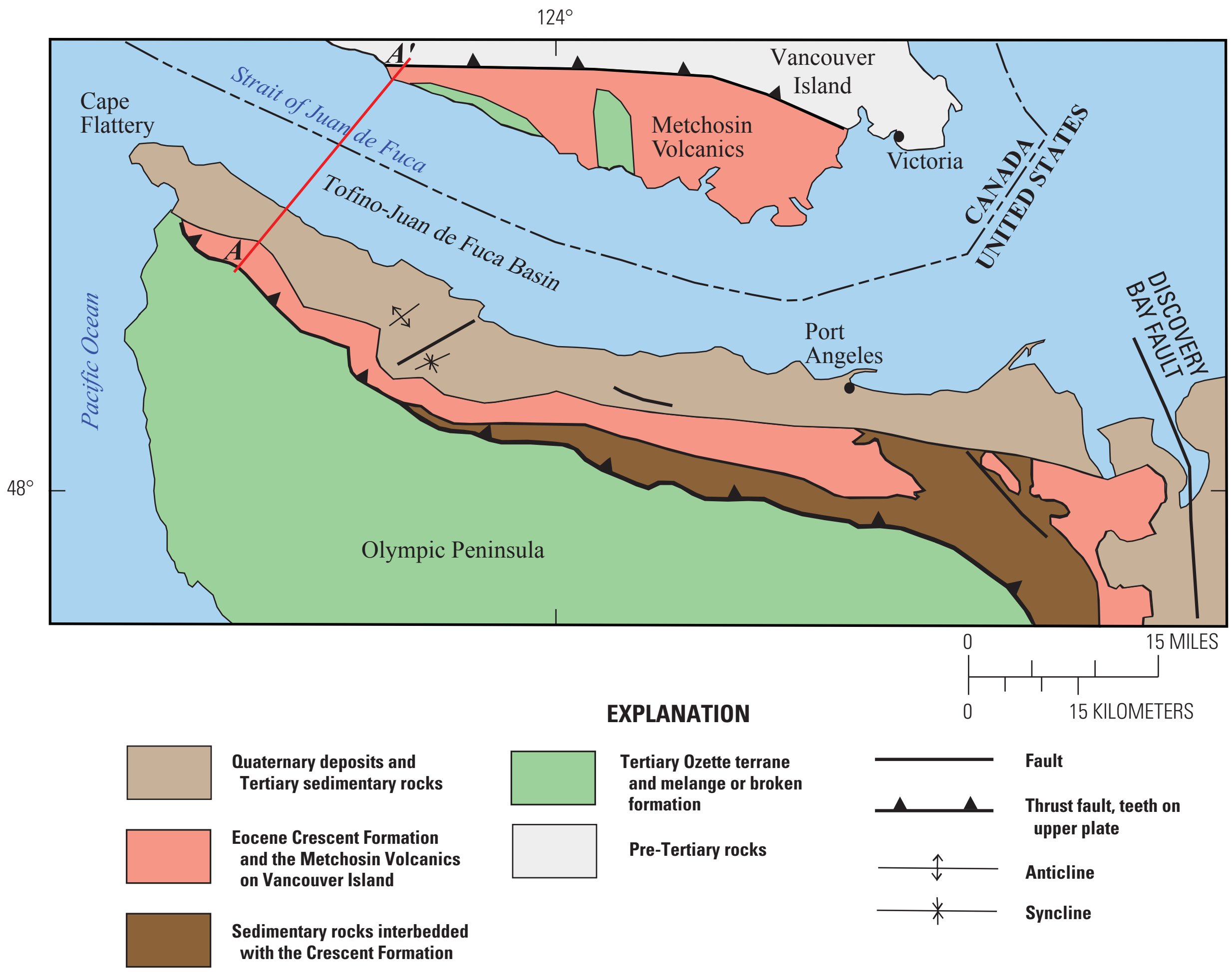

Figure 46. Generalized geologic map of the northern part of the Olympic Peninsula, Vancouver Island, Canada, and the Tofino-Juan de Fuca Basin. Cross section A–A' shown in figure 48. Modified after Tabor and Cady (1978a), Niem and Snavely (1991), and Johnson and others (1997).

cooling of the Crescent Formation basement rocks (Johnson and others, 1997). In the southern part of the basin, there are more than 28,000 ft of northward-dipping rocks of middle Eocene to early Miocene age (figs. 47 and 48) (Brown and others, 1960; Gower, 1960; Snavely and others, 1980; Snavely, 1983; Snavely and others, 1993b; Schasse, 2003), including lithic arkosic to lithic turbidite sandstone and deep-marine mudstone and minor amounts of conglomerate and sedimentary breccia. The middle to upper Eocene Aldwell Formation (fig. 47), which unconformably overlies the oceanic basalt of lower Eocene Crescent Formation oceanic basalt, is predominantly marine mudstone and siltstone with minor amounts of sandstone, conglomerate, and lenses of pillow basalt, volcanic breccia, and tuff; average thickness is 2,000 ft (Brown and others, 1960). The Aldwell Formation is overlain unconformably by the upper Eocene Lyre Formation, at least 2,200 ft thick, consisting of massive, medium- to coarse-grained conglomerate and interstratified gray to grayish-brown, coarse-grained, massive sandstone with pebbly conglomerate beds and minor thin-bedded siltstone and shale. Snavely and others (1978) divided the overlying Twin River Group (fig. 47) into the Hoko River, Makah, and Pysht Formations, with combined thicknesses as much as 17,500 ft. The Hoko River Formation conformably overlies, or intertongues with, the Lyre Formation and ranges in thickness from 5,250 to 7,550 ft; it contains fossiliferous siltstone with interbedded phyllitic and basaltic sandstone, pebbly sandstone, and conglomerate (Snavely and others, 1978, 1980; Prothero and others, 2009). The Hoko River Formation is gradationally or locally unconformably overlain by 7,550 to 9,200 ft of the Makah Formation, which consists of turbidite sandstone and siltstone. The Makah Formation is gradationally or unconformably overlain by 3,610 to 4,590 ft of the Pysht Formation and contains gray to olive-gray massive mudstone, sandy siltstone with minor interbeds of sandstone, and conglomerate channels. The Pysht Formation is overlain by the lower Miocene Clallam Formation, which forms the upper part of the sedimentary sequence that filled the deep-marine Juan de Fuca Basin (fig. 47) (Niem and

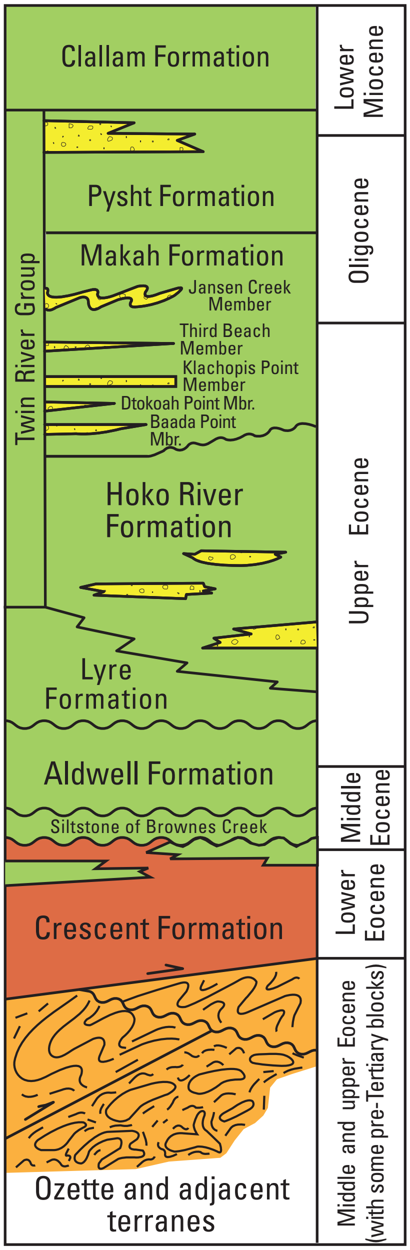

Figure 47. Stratigraphic column showing rocks of the Tofino-Juan de Fuca Basin, northwest Washington, and Vancouver Island, Canada. Modified after Snavely and others (1978), Niem and Snavely (1991), and Snavely and others (1993). Not to scale.

Snavely, 1991). The Clallam Formation ranges in thickness from 1,970 to 2,625 ft (Addicott, 1976) and contains predominantly marine sandstone, sandy siltstone, and conglomerate, with thin coal beds and carbonaceous mudstone and siltstone in the upper part of the formation. The Crescent Formation and the middle to upper Eocene Ozette terrane (figs. 47 and 48) along the southern part of the basin, have been underthrusted by the melange and broken formation terranes of the Olympic Peninsula (Tabor and Cady, 1978a; Schasse, 2003).

Sedimentary rocks in the Tofino-Juan de Fuca Basin represent several depositional environments (Niem and Snavely, 1991). The bathyal slope, outer fan, and basin-plain environments are indicated by thick mudstone units with minor distal turbidites represented by the middle and upper Eocene Aldwell and the Oligocene and lower Miocene Pysht Formations (Snavely and others, 1978; Snavely, 1983). The submarine-fan and gravel-slope wedges include the Lyre Formation (fig. 47) and informal upper Eocene Cape Flattery breccia (Brown and others, 1956; Ansfield, 1972). Slope and basin turbidite flows and middle to outer fan conglomerate channels are identified in the upper Eocene Hoko River Formation (Ansfield, 1972; De Chant, 1989), with turbidite fans in an outer- to mid-fan environment identified in the upper Eocene to lower Miocene strata of the Makah and Pysht Formations (Brown and Gower, 1958; Rau, 1964; Snavely and others, 1980). The marine units in the basin were mostly derived from (1) Paleozoic and Mesozoic low-grade metamorphic, granitic, and volcanic rocks, and eroded sedimentary-sourced terranes on the southern part of Vancouver Island (Snavely and others, 1980; Niem and Snavely, 1991); and (2) local lower Eocene Crescent Formation and Metchosin Volcanics (figs. 4 and 46) (Brown and others, 1960; Snavely, 1983). The Clallam Formation was deposited mostly as a marine unit with the upper part deposited in a coal-bearing deltaic environment.

The central and western part of the Olympic Peninsula is characterized as accretionary terrane (fig. 3) that formed during convergence between the Pacific and North American plates during late Eocene and middle Miocene time, producing two melange terranes. The absence of blueschist-facies rocks and ultramafic rocks is further evidence that the Olympic core rocks were accreted and subducted and mixed with mantle material (Tabor and Cady, 1978b). The only onshore exposures of the terranes are within the western part of the Olympic Peninsula, where they were transported eastward to form the core of the Olympic Mountains west of the Hurricane Ridge fault (figs. 38, 49, and 50). Surrounding this core area is a rim-shaped area of peripheral rocks consisting of lower to middle Eocene oceanic basalt and volcaniclastic rocks of the Crescent Formation (figs. 7 and 51) overlain by sedimentary rocks of Eocene to Miocene age. The two terranes in the western part of the Olympic core are known as the Ozette terrane that formed during the late Eocene convergence and the Hoh rock assemblage that formed during the late Oligocene to middle Miocene convergence (fig. 51) (Rau 1975, 1979; Tabor and Cady, 1978b; Snavely and Kvenvolden, 1989). The two terranes, both of which contain organic-rich rocks, have

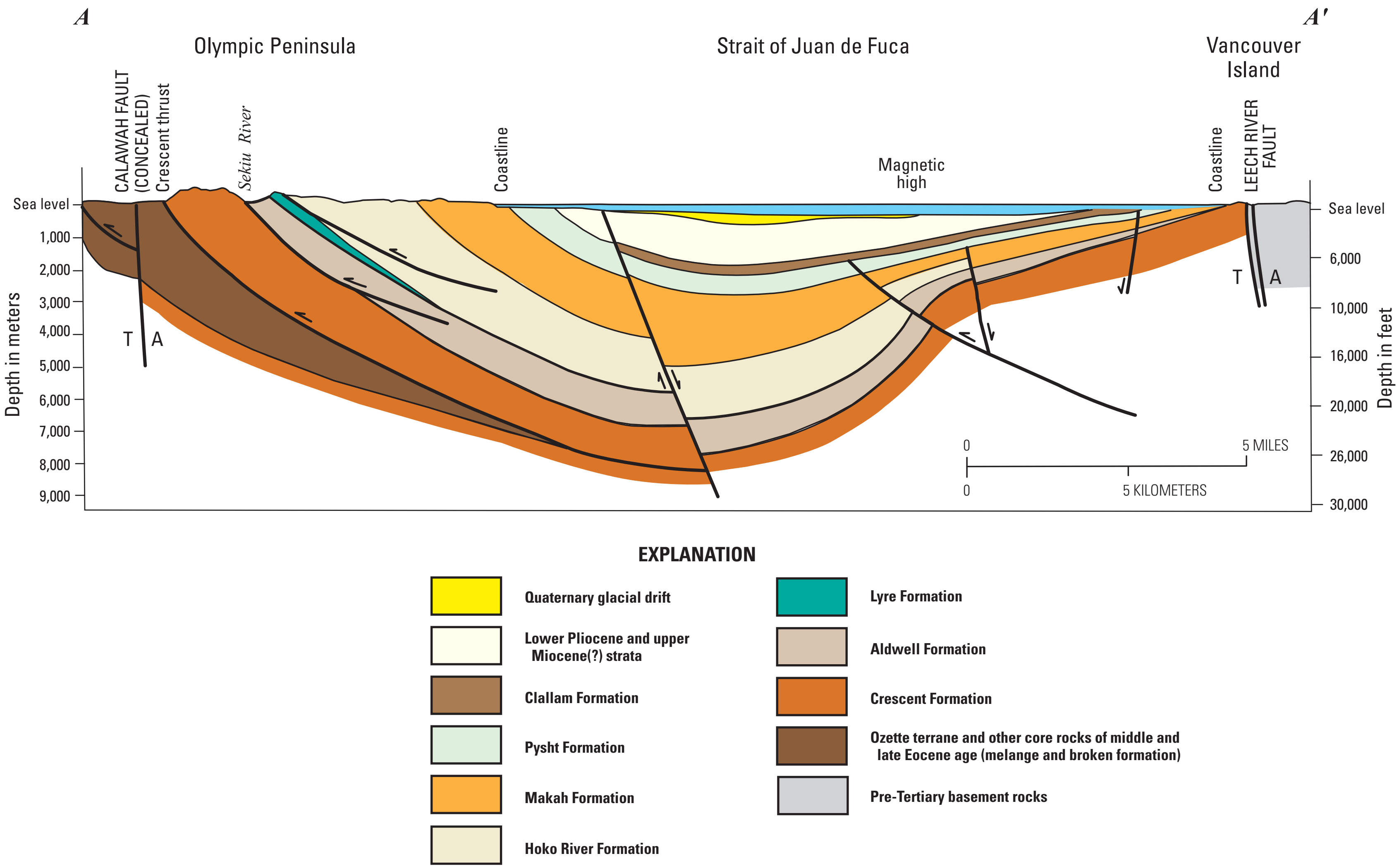

Figure 48. Generalized structure cross section of the Tofina-Juan de Fuca Basin across Strait of Juan de Fuca extending from the northern part of the Olympic Peninsula to the southern part of Vancouver Island, Canada. Location of cross section shown in figure 46. Modified after Snavely (1983) and Niem and Snavely (1991).

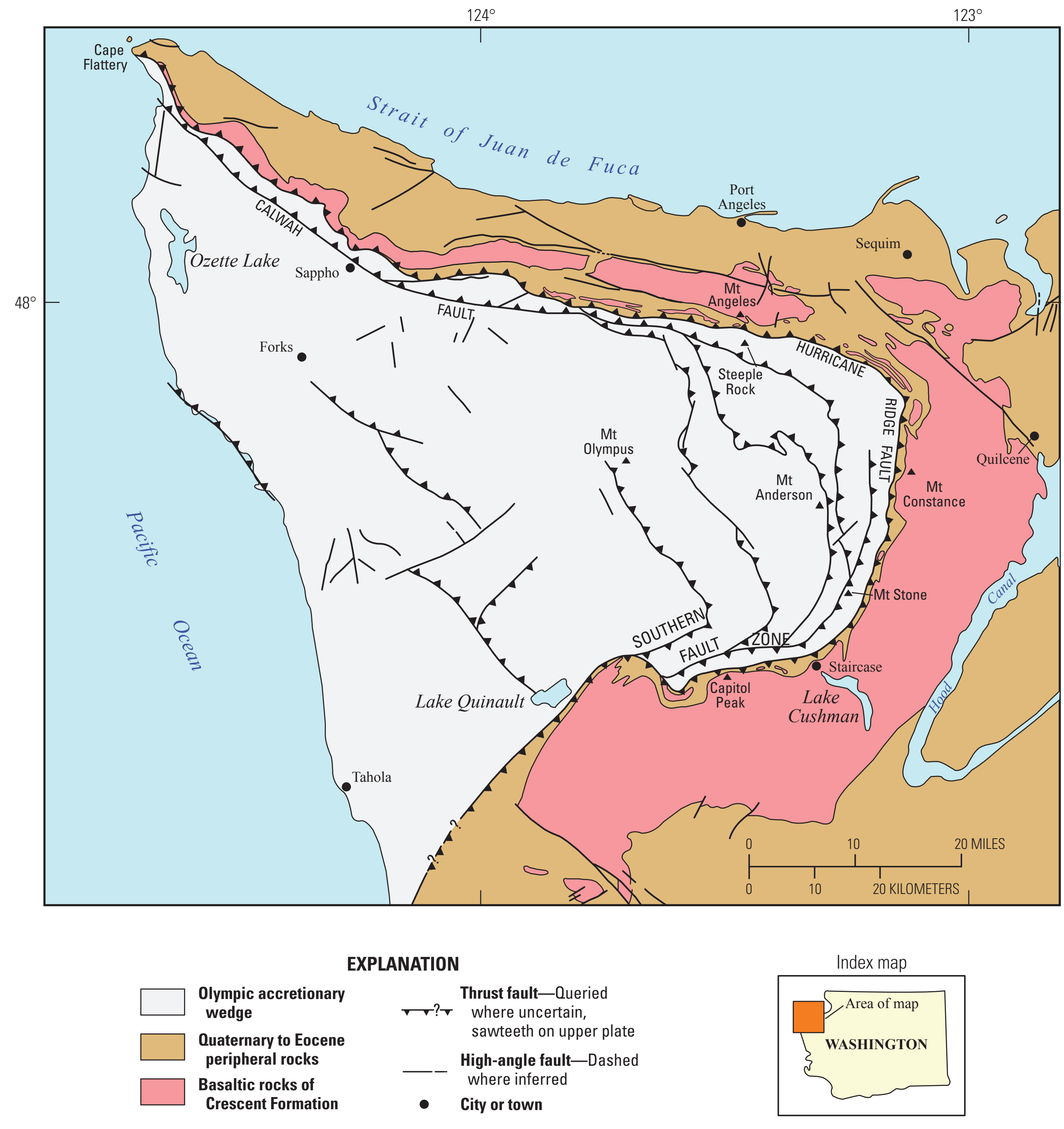

Figure 49. Generalized geologic map showing major rock units and faults on the Olympic Peninsula. Modified after Tabor and Cady (1978b).

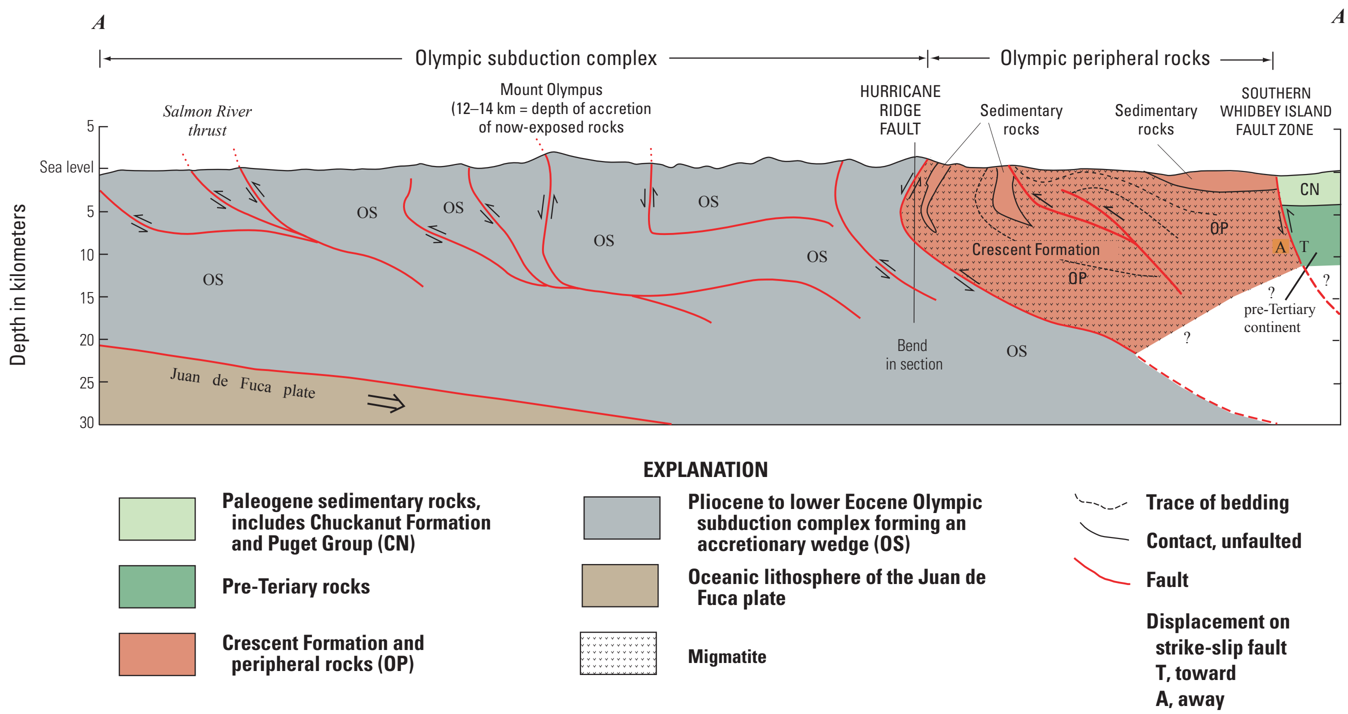

Figure 50. Structure cross section showing the lower Eocene to Pliocene Olympic subduction complex that formed an accretionary wedge on the Olympic Peninsula, the Olympic peripheral rocks, and the Paleogene sedimentary rocks of northwest Washington. Location of section is in figure 38. Modified from Tabor and Cady (1978b), Johnson and others (1996), Brandon and others (1988), and Brown and Dragovich (2003).

been differentiated on the basis of biostratigraphic data. The Ozette melange (fig. 51), of unknown thickness, includes lithic sandstone and siltstone turbidite beds and minor conglomerate, coal, and carbonaceous sandstone and siltstone. The Hoh rock assemblage (fig. 51) includes at least 8,200 ft of lithic feldspathic sandstone and siltstone turbidite beds (figs. 52 and 53) and minor amounts of conglomerate, coal, and carbonaceous sandstone and siltstone (Snavely and Kvenvolden, 1989).

Southwestern Washington Area

The oldest rocks exposed in southwestern Washington are Paleogene in age and include the Crescent Formation, the lower part of the Hoh rock assemblage, and the McIntosh, Cowlitz, and Lincoln Creek Formations (figs. 5 and 54) all of which are described in previous sections for other areas in which they are present. The post-Crescent Formation Tertiary rocks are about 15,000 ft thick in the Grays Harbor and Willapa Bay areas and to the east (Rau, 1967, 1968).

The upper Eocene to Oligocene Lincoln Creek Formation (fig. 8) consists mostly of marine tuffaceous mudstone, siltstones, and fine-grained sandstones ranging in thickness from 2,000 to more than 9,000 ft in southwest Washington (Rau, 1966, 1967; Beikman and others, 1967). The siltstone and silty sandstone beds are thick, displaying little bedding except where tuff or concretionary layers are present. Some altered tuff beds have been identified in the Lincoln Creek Formation ranging in thickness from a few inches to a few feet (Rau, 1967).

Shallow marine and deltaic rocks, of the lower to middle Miocene Astoria Formation and the middle to upper Miocene Montesano Formation, crop out in southwest Washington (fig. 54). The Astoria Formation unconformably overlies the Lincoln Creek Formation in areas to the east where structural highs are present, but the two are conformable elsewhere. The Astoria Formation is estimated to be about 3,500 ft thick northeast of Grays Harbor and consists of marine organic-rich mudstones, siltstones, and fine- to coarse-grained lithic-feldspathic and arkosic sandstones with minor conglomerates (fig. 44) (Rau, 1967; Walsh and others, 1987). The rocks of the Astoria Formation are commonly massive but include locally sourced conglomerate and concretionary beds. The Astoria Formation can be differentiated from the underlying Lincoln Creek Formation by the increase in carbonaceous material, the lack of tuffaceous material, and generally having better bedding.

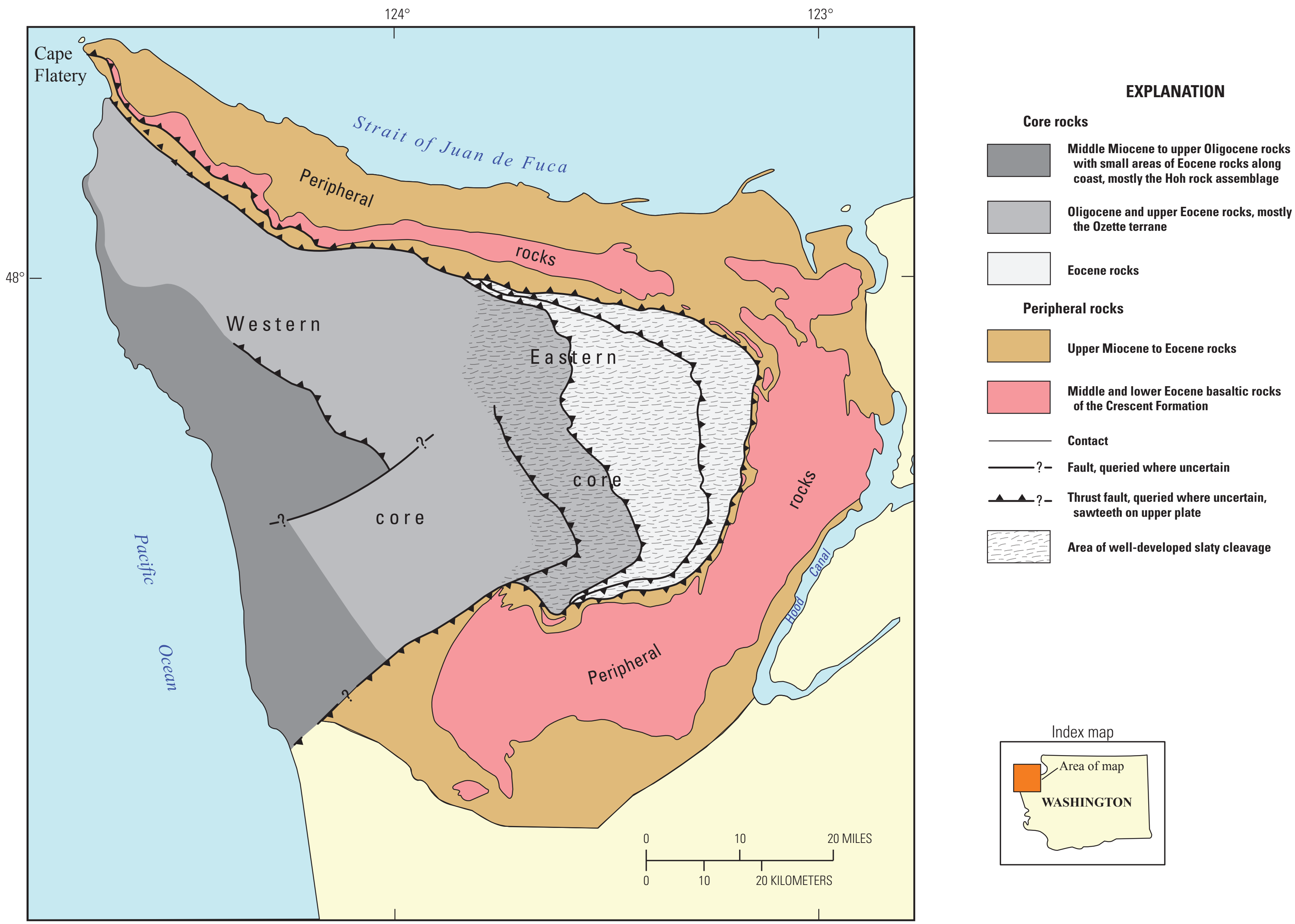

Figure 51. Map showing the different core terranes and peripheral rocks on the Olympic Peninsula. Modified after Tabor and Cady (1978b).

Figure 52. Outcrop of the upper Oligocene to middle Miocene Hoh rock assemblage turbidites along Beach 4, Washington coastline. The top surfaces of the beds face to the left, indicating that the beds are overturned.

Figure 53. Close-up view of the upper Oligocene to middle Miocene Hoh rock assemblage turbidites along Beach 4, Washington coastline. Parallel laminated sandstones below and right of knife. Top surfaces of the beds face to the left, indicating that the beds are overturned.

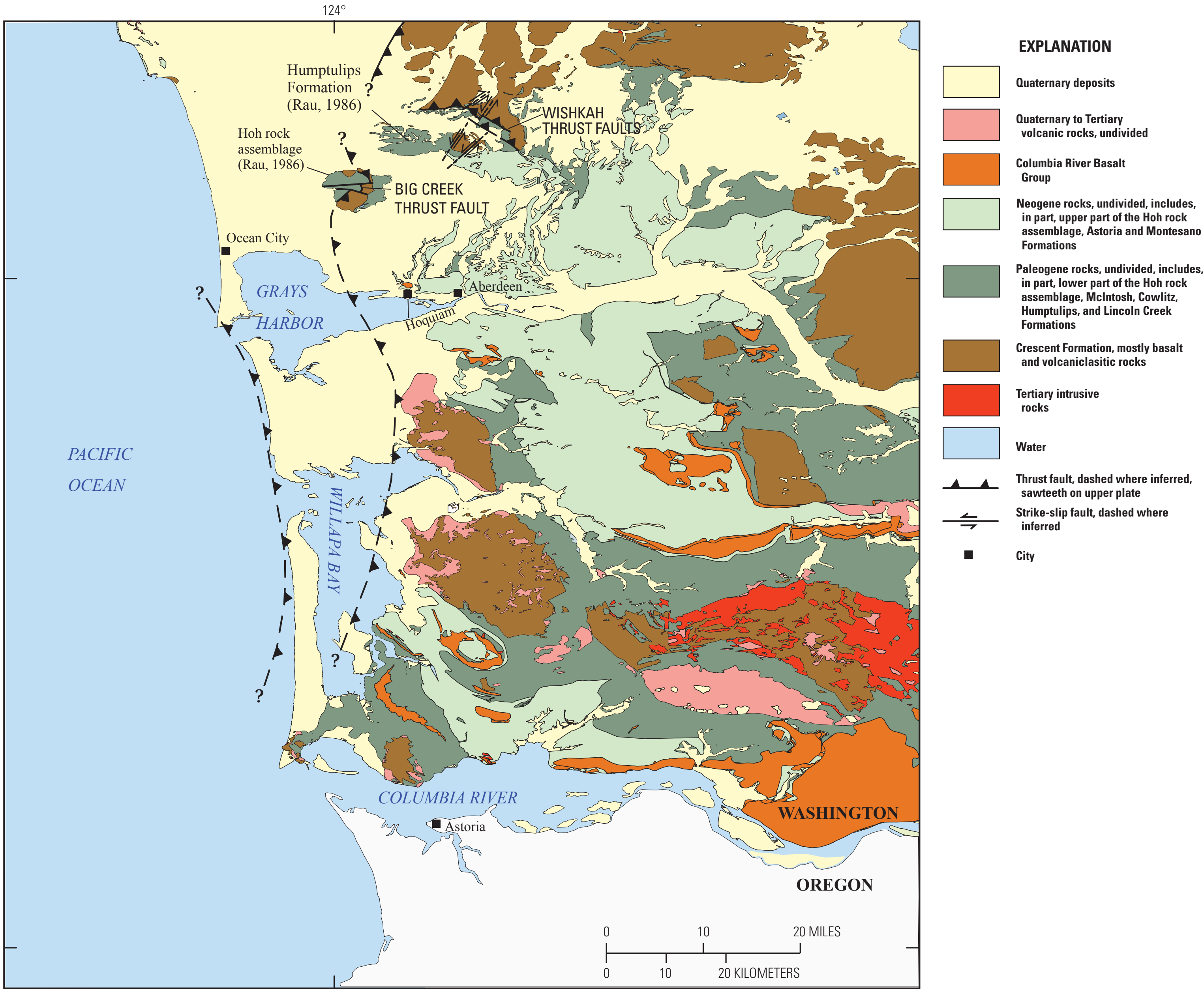

Figure 54. Geologic map of southwestern Washington showing selected geologic units. Modified after Rau (1986), Walsh and others (1987), Snavely (1987), and Palmer and Lanley (1989).

The Miocene Montesano Formation unconformably overlies the Astoria Formation, is as much as 2,500 ft thick (Rau, 1967), and occurs over a large area surrounding Aberdeen, Wash. (fig. 54). The lower part of the Montesano Formation consists of about 1,500 ft of fine-grained sandstone (fig. 55) with minor amounts of conglomerate and mudstone; the upper part consists of about 1,000 ft of tuffaceous mudstone and sandy siltstone (Fowler, 1965, 1966). East of Grays Harbor, the Montesano Formation averages 1,800 ft thick and is composed mostly of fine- to medium-grained sandstone, pebbly sandstone, and conglomerate, indicating a probable sediment source area to the east.

Several periods of deformation occurred in southwestern Washington since the middle Eocene, resulting from convergence of the Pacific and North American plates. These included the tectonic processes of crustal shortening, thrust and strike-slip faulting, and block rotation (Wells and Coe, 1985; Rau, 1986). The first period of deformation resulted in the late middle to early late Eocene underthrusting of the organic-rich Hoh rock assemblage, and possibly also the Ozette melange, beneath the Crescent Formation along the Big Creek thrust fault (fig. 54) (Rau, 1986; Snavely and Kvenvolden, 1989; Snavely and others, 1993b). Contemporary with this thrusting event, east–west strike-slip faulting offset both rock assemblages and the Crescent Formation. The Big Creek thrust fault (fig. 54) was interpreted as a middle Tertiary plate boundary by Johnson and others (1997, their fig. 10); they placed the boundary along the eastern edge of Grays Harbor. Snavely and Wagner (1982) and Snavely (1987), however, placed this plate boundary just offshore (westernmost thrust fault in fig. 54); west of the plate boundary (fig. 56, fault A), the Miocene shallow-marine rocks of the Montesano Formation were deposited on the lower plate, which consists of the Hoh rock assemblage (Rau, 1973) and possibly the rocks of the Ozette terrane (Snavely and Wagner, 1982); Snavely, 1987; Snavely and others, 1993b). To the east of the plate boundary of Snavely and Wagner (1982, 1987), the Astoria and Montesano Formations were deposited over the Crescent Formation on the upper plate (fig. 56). The southern extension of the Big Creek thrust fault may be fault B of Snavely and Wagner (1982) and Snavely (1987) (fig. 56), and the Hoh rock assemblage could be present below the Crescent Formation at depth, but the lack of onshore seismic reflection profiles limit the deeper projection of geologic formations (fig. 56).

The second major period of deformation occurred in the middle Miocene and resulted in faulting along the Wishkah thrust faults and folding within the Humptulips and Astoria Formations, but did not affect the upper Miocene Montesano Formation (figs. 54 and 55) (Rau, 1986). Strike-slip faults offset the Crescent and Humptulips Formations during the same deformation period. The third period of deformation followed the deposition of the Miocene Montesano and resulted in gentle folding and minor faulting. Figure 56 shows the

Figure 55. Exposure of arkosic sandstone and siltstone in the middle to upper Miocene Montesano Formation in road cut along U. S. Highway 12, east of Aberdeen, Washington (see fig. 54).

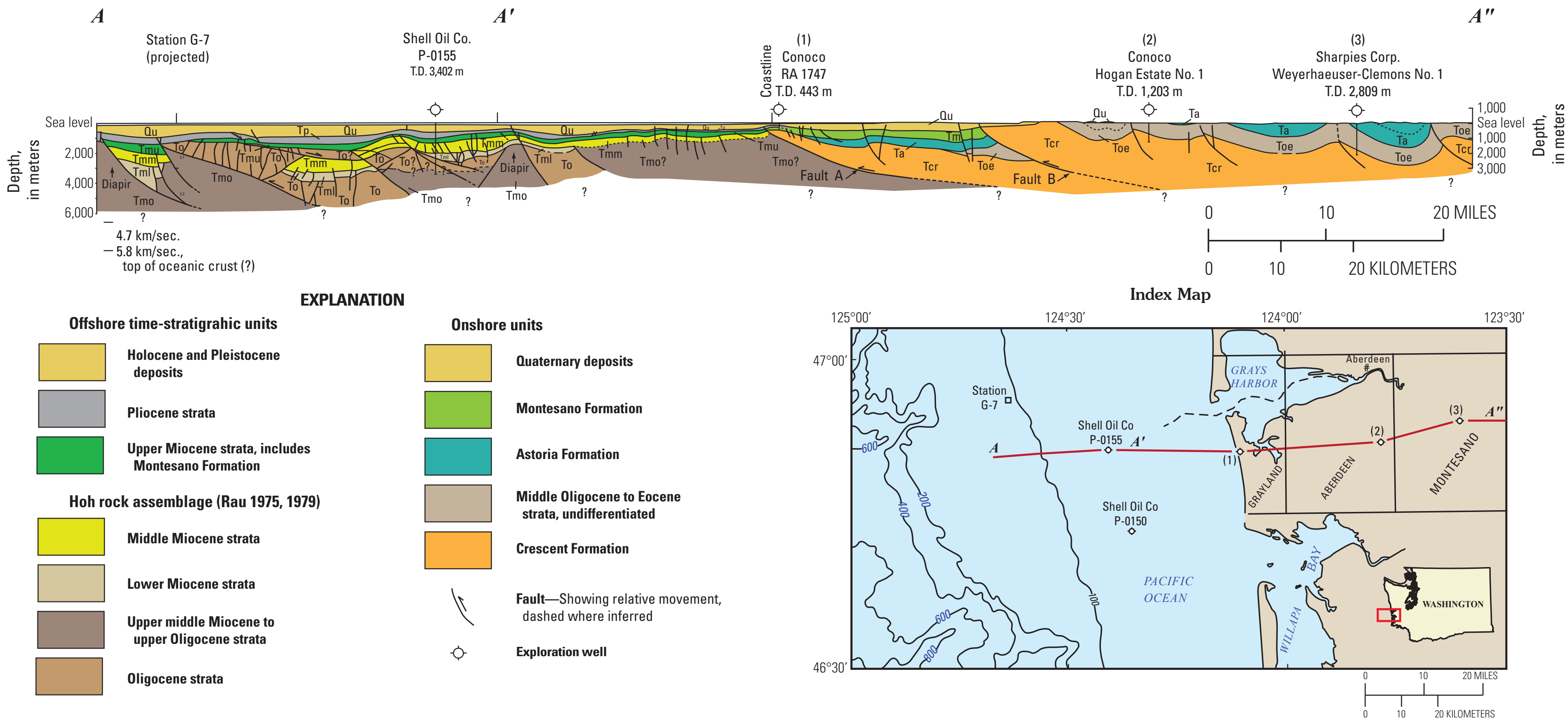

Figure 56. Structure cross section across part of the inner continental shelf and adjacent Coast Range of southwestern Washington. Offshore geology between *A* and *A*′ based on interpretation of 24-channel seismic data and subsurface data from Shell Oil Company exploration well P-0115 (see index map). Onshore Quaternary and Tertiary unit symbols include: Qu, Quaternary deposits; Tm, Montesano Formation; Ta, Astoria Formation; Toe, undivided middle Oligocene to Eocene units; Tcr, Crescent Formation. Offshore time-stratigraphic units include: Qu, Holocene and Pleistocene deposits; Tp, Pliocene strata; Tmu, upper Miocene strata; Tmm, middle Miocene strata; Tml, lower Miocene strata; Tmo, upper middle Miocene to upper Oligocene strata; To, Oligocene strata. Units Tmm, Tml, Tmo, and To are assumed melange and broken formation equivalent to the Hoh rock assemblage of Rau (1975, 1979). Modified after Snavely and Wagner (1982) and Snavely (1987).

complex thin-skinned structure associated with these periods of deformation in southwestern Washington.

Eocene Coal-Bearing Depositional Systems of Western Oregon and Washington

Eocene coal-bearing rocks of western Oregon and Washington are included in a variety of stratigraphic units that bear different names in different parts of the Western Oregon and Washington Province. This abundance of stratigraphic names is a reflection of the many different but largely uncoordinated geologic investigations that have taken place in the various areas, as well as a consequence of the intertonguing relations in different areas between sedimentary rocks and intrabasinal volcanic rocks in the province. Despite the different names, it is important to recognize that all these stratigraphic units were deposited in a single regional coal-depositional system that extended north–south along depositional strike from the Bellingham area in northwestern Washington south to the Coos Bay area in southwestern Oregon (fig. 57) (Dott, 1966). At times, this regional depositional system was segmented by faults and local volcanic centers. Additionally, the intrabasinal Tukwila and Northcraft volcanic centers (Tukwila and Northcraft Formations, respectively, fig. 5) had important effects on the Washington part of the Eocene coal-bearing architecture and facies patterns (Buckovic, 1979). Paleobotanic studies (Wolfe, 1968, 1978, 1981, 1994, 1995; Burnham, 1994; Retallack and others, 2004) indicate that during the Eocene, the province coastal climate was warm, humid to mesic, and subtropical.

Eocene coal-bearing rocks of western Washington are included in a variety of stratigraphic units including the Carbonado, Chuckanut, Cowlitz, Renton, Skookumchuck, Spiketon, and Tiger Mountain Formations, and the undivided Puget Group (fig. 5) (Brownfield and others, 1994). In Oregon, coal-bearing units are the Bateman, Coaledo, Cowlitz, Spencer, and Tyee Formations and the Umpqua Group (fig. 8).

Paleocurrent data indicate that sediment transport was from east to west across western Washington (Buckovic, 1979; Brownfield and others, 1994, 2005). Middle to upper Eocene sandstones are generally arkosic (Buckovic, 1979; Frizzell, 1978; Johnson, 1985; Heller and Ryberg, 1983; Wells and others, 2000; Ryu, 2003), the source being crystalline rocks to the east; the proportion of volcanic detritus generally increases upward in the section, but also varies locally as a function of proximity to volcanic centers.

Coal-bearing formations in western Oregon and Washington were deposited in a variety of fluvial, deltaic, brackish, and shallow-marine environments (for example, Allen and Baldwin, 1944; Baldwin and others, 1973; Buckovic, 1979; Armentrout, 1980; Burnham, 1990; Brownfield and others, 1994, 2005; Flores and Johnson, 1995). Fluvial and distributary channel deposits typically form thick crossbedded sandstone bodies. Interchannel deposits comprise a variety of sandstone, mudstone, and coaly facies deposited in crevasse channels and splays, floodbasins, shallow lakes, and mires. Shallow-marine and brackish-water deposits consist mainly of stratified to massive (from bioturbation) sandstone and mudstone deposited in tide- and wave-influenced shoreface, mouthbar, and shallow-shelf environments. Coals are bracketed by both nonmarine and brackish or shallow-marine facies and developed in both upper and lower delta and coastal-plain settings.

Following sedimentological models of Ryer (1984) for Cretaceous rocks in the Rocky Mountains, the general upward thinning of the coal beds exposed in the coal-bearing areas in

Figure 57. Paleogeographic map showing the peat-bearing coastal plain of western Oregon and Washington during middle to late Eocene time. Feldspathic-quartzose sands, derived from eastern granitic terranes, were transported westward in several river systems to a broad coastal plain bordering a shelf-margin sea. Coal swamps developed from Bellingham to Coos Bay. Volcanism within the sediment source terrain, along the coastal margin, and on nearshore islands provided volcaniclastic sediments. Modified after Dott (1966) and Armentrout and Suek (1985).

the province is consistent with their deposition during a major transgressive pulse along the Eocene coastline of southwest Washington.

Tectonic Evolution of the Pacific Northwest

Paleomagnetic studies of lower Eocene to Miocene volcanic and sedimentary rocks in the Oregon and Washington Coast Range (fig. 58) demonstrate that this crustal block rotated from 75° to 80° clockwise with respect to the North American plate since the early Eocene (Simpson and Cox, 1977; Heller and Ryberg, 1983; Wells and Coe, 1985; Wells and Heller, 1988; England and Wells, 1981; Wells and others, 2000). This rotation of the Coast Range may still be occurring, with the extension of the northern part of the Basin and Range region (Wells and Heller, 1988; Wells and others, 1998). The lower to middle Eocene Tyee Formation (fig. 12) is rotated about 67° clockwise (Simpson and Cox, 1977), and its onlap onto the Klamath terrane indicates that the rotation postdates the accretion of the Siletz terrane to the continent (Heller and Ryberg, 1983; Wells and others, 2000). Wells and others (2000) reported that the Paleogene Umpqua Group fold axis formed prior to the deposition of the Tyee Formation, therefore the 67° of rotation measured in the Tyee rocks must have occurred after the deformation of the Umpqua Group. The Eocene Tillamook Volcanics in the north-central Oregon Coast Range have been rotated clockwise about 46° (Magill and others, 1981), but volcanic rocks in the northern part of the Washington Coast Range were rotated much less. Samples from the lower Eocene Crescent Formation collected in the Black Hills west of Olympia, Wash., have measured clockwise rotations of about 27° (Globerman and others, 1982), and the Eocene volcanic rocks at Bremerton west of Seattle have measured clockwise rotations of about 7° (Beck and Engebretson, 1982). The middle Miocene flood basalts of the Columbia River Basalt Group are the youngest rocks with measured rotations; these show a clockwise rotation of 15° to 25° when compared to similar flows on the Columbia Plateau (Wells and Heller, 1988).

Several tectonic models have been proposed to explain the large Tertiary clockwise rotations of crustal blocks in the Pacific Northwest. The proposed models consist of three major rotation concepts or the combination of two or more of the concepts: (1) microplate rotation during accretion of allochthonous Coast Range marginal terranes (Simpson and Cox, 1977; Duncan, 1982), (2) rotation induced by dextral shear between the continent and oceanic plates to the west (fig. 59) (Beck, 1976, 1980; Wells and Coe, 1985; Wells and Heller, 1988), and (3) rotation of terranes in front of differential continental extension in the Basin-and-Range Province region (Simpson and Cox, 1977; Hammond, 1979). Wells and Heller (1988) proposed a two-fold model that incorporates both dextral shear and continental extension in the Basin-and-Range region with little or no clockwise rotation related to the accretion of the early Eocene oceanic plates. The majority of the eastward rotation postdates the accretion and deformation of the lower Eocene Siletz terrane against the North American plate. Paleogeographic reconstructions based on the Wells and Heller (1988) model are shown in figure 59.

The late middle to late Eocene was a transitional period representing the last phases of the episode of rifting and strike-slip faulting prior to initiation of Cascade-arc volcanism. During this time, basin subsidence slowed significantly and coal-bearing sedimentary units (fig. 57) were deposited in fluvial, deltaic, and shallow-marine environments over the western basement terranes.

Cretaceous-Tertiary Composite Total Petroleum System (500401)

A total petroleum system (TPS)—the Cretaceous-Tertiary Composite TPS—is defined within the Western Oregon and Washington Province (fig. 1) and was first defined during an assessment of gas resources in the Eastern Oregon and Washington Province by Brownfield (2008). The TPS boundary is defined on the basis of where potential reservoir and source rocks are known to exist or inferred to exist, and where hydrocarbon source-rock thermal maturities have reached a vitrinite reflectance (R_O) of 0.5 percent or greater. Gas generated from potential source rocks is interpreted to have migrated into Paleocene to Miocene reservoir rocks.

As defined, the TPS most likely underlies much of the Eastern Oregon and Washington Province and extends westward under the Cascade Range (fig. 1) obscuring and (or) separating many of the stratigraphically equivalent basins containing potential Paleogene hydrocarbon source rocks in both Oregon and Washington. That part of the TPS, described and assessed by Brownfield (2008), includes thick successions of Cretaceous to Oligocene fluvial to deltaic arkosic sandstone and interbedded mudstone, carbonaceous shale, and coal. These strata are in (1) the Eocene Swauk, Manastash, Teanaway, Chumstick, and Roslyn Formations and the Oligocene Wenatchee and Ohanapecosh Formations in Washington; and (2) the Cretaceous Hudspeth and Gable Creek Formations, the Paleocene to Eocene "Herren formation" of Shorey (1976), and the Eocene to lower Oligocene Clarno Formation in Oregon.

The western part of the Cretaceous-Tertiary Composite TPS includes thick Paleogene fluvial to deltaic arkosic sandstone and interbedded mudstone, carbonaceous shale, and coal as much 20,000 ft thick (Johnson, 1985). These strata, although widespread, are primarily restricted to disconnected basins throughout the TPS area (Frizzell, 1978, 1979; Johnson, 1982; Johnson, 1984a,b; Johnson, 1985; Johnson and Tennyson, 1995; Brownfield, 2008).

The Chuckanut Formation (fig. 5) in the Bellingham Basin and coal field (figs. 2 and 40) may be stratigraphically

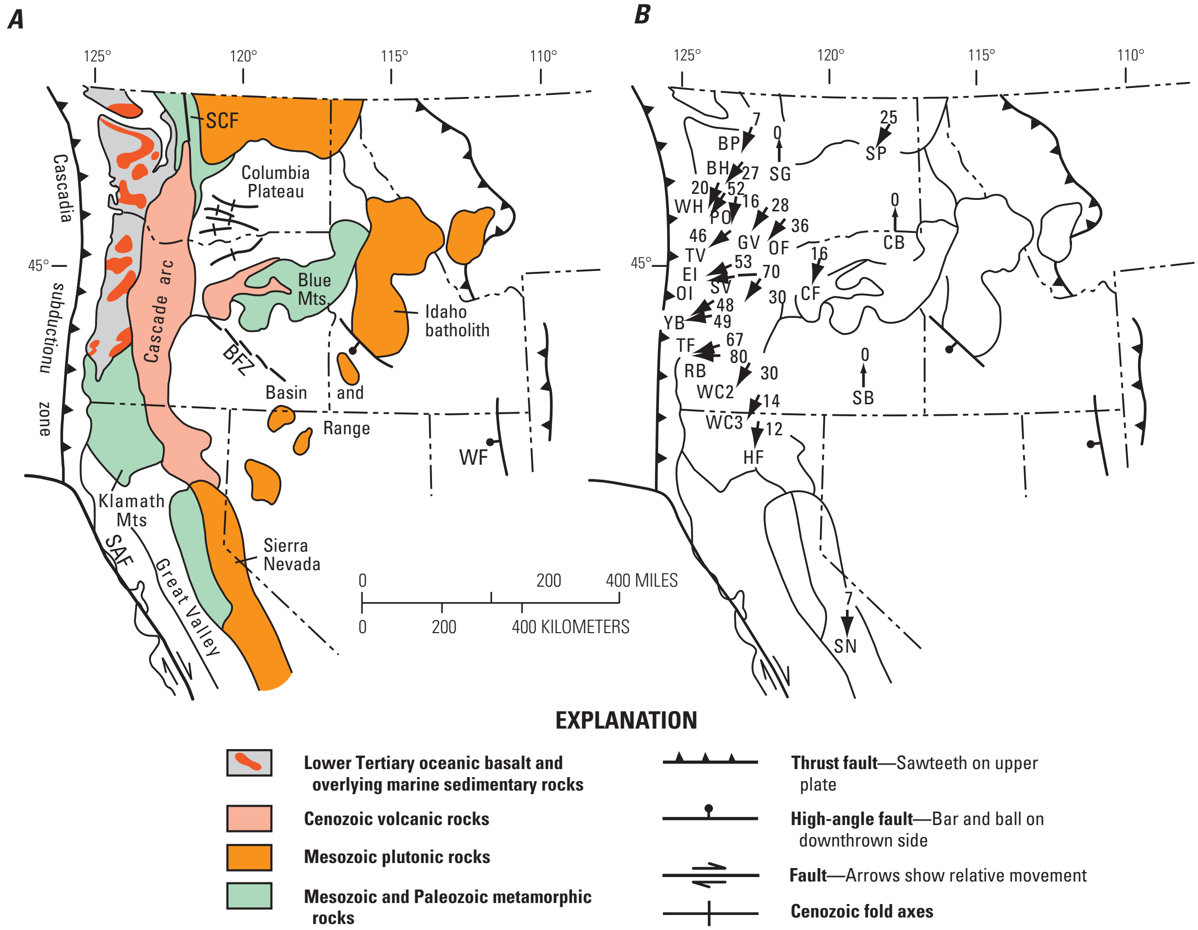

Figure 58. Geologic provinces and paleomagnetic-rotation data of the Pacific Northwest. *A*, Geologic provinces of the Pacific Northwest, modified from King and Beikman (1974); SAF, SCF, BFZ, and WF represent San Andreas fault, Straight Creek fault, Brothers fault zone, and Wasatch fault, respectively. *B*, Tectonic rotations of rock units, in degrees, modified from compilations by Grommé and others (1986), Magill and others (1981), and Bates and others (1981); shaded arrows indicate 95 percent confidence limits on rotations. Washington locations: BP, Eocene volcanic rocks at Bremerton-Port Ludlow (Beck and Engebretson, 1982); BH, Eocene Crescent Formation, Black Hills (Globerman and others, 1982); WH, Eocene Crescent Formation, Willapa Hills (Wells and Coe, 1985); GV, upper Eocene Goble Volcanics (Beck and Burr, 1979; Wells and Coe, 1985); PO, Miocene Pomona Member, Saddle Mountains Basalt (Magill and others, 1982); OF, upper Eocene and Oligocene Ohanapecosh Formation of Bates and others (1981); SG, Miocene Snoqualmie and Grotto batholiths (Beske and others, 1973); SP, Eocene Sanpoil Volcanics (Fox and Beck, 1985). Oregon locations: TV, Eocene Tillamook Volcanics (Magill and others, 1981); EI, Eocene intrusions (Beck and Plumley, 1980); OI, Oligocene intrusions (Beck and Plumley, 1980); SV, Eocene Siletz River Volcanics (Simpson and Cox, 1977); TF, Eocene Tyee Formation (Simpson and Cox, 1977); RB, Paleocene basalt at Roseburg (Wells and others, 1985); YB, upper Eocene Yachats Basalt (Simpson and Cox, 1977); WC2, WC3, Oligocene and Miocene volcanic rocks of the western Cascade Range (Magill and Cox, 1980; Beck and others, 1986); CF, Eocene and Oligocene Clarno Formation (Grommé and others, 1986); CB, Miocene Columbia River Basalt Group; and SB, Miocene Steens Basalt (Mankinen and others, 1987); California locations: HF, Lower and Upper Cretaceous Hornbrook Formation (Mankinen and Irwin, 1982); SN, Late Cretaceous Sierra Nevada batholith (Frei and others, 1984).

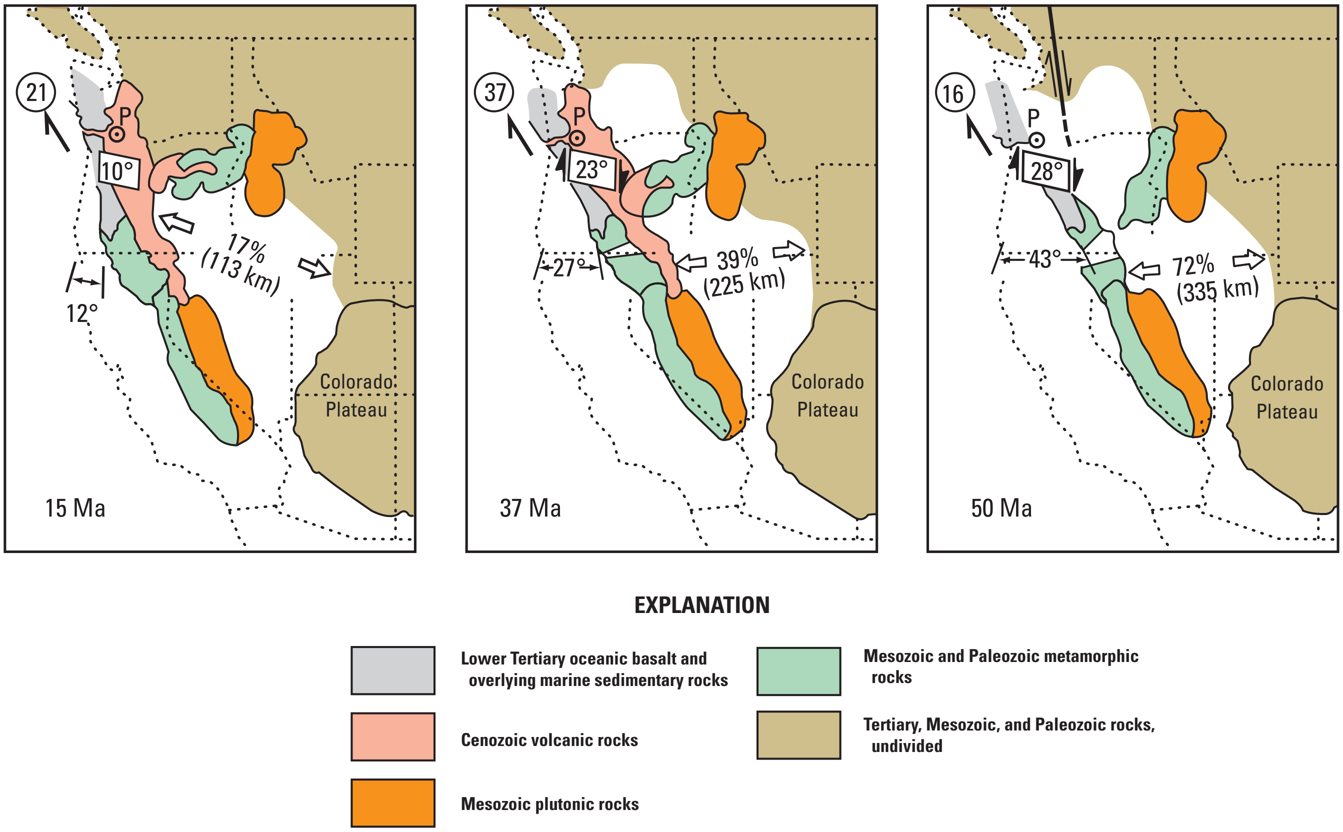

Figure 59. Continental reconstructions at 15, 37, and 50 Ma, based on paleomagnetic and geologic constraints. Rotation due to dextral shear (in boxes) was subtracted from western Oregon and Washington rotations before restoration of crustal blocks about Euler pole, P (Frei and others, 1984). Resultant block rotations are shown, along with amounts of northern Basin-and-Range extension required to produce them. Component of Farallon plate motion parallel to continental margin shown in circle in kilometers per million years (Engebretson and others, 1985). Modified after Wells and Heller (1988).

equivalent to the Swauk, Roslyn, and Chumstick Formations in eastern Washington (Johnson, 1985). Johnson (1984b) inferred a rapidly uplifted crystalline source area to the east, but the arkosic sandstone petrography of the Chuckanut Formation is similar to the Swauk, Roslyn, and Chumstick Formations (Frizzell, 1978; Johnson, 1984a; Johnson, 1985) indicating a probable connection between the basins. Frizzell (1978) also suggested that the Chuckanut and Swauk Formations (current outcrop areas) might have been joined, then later separated by the Straight Creek fault zone (fig. 38). Other equivalent or partly equivalent rocks to the Chuckanut Formation extend southward in western Washington and include the Puget Group (fig. 5) in the Green River coal field (fig. 2), the Carbonado Formation in the Wilkeson-Carbonado coal field, and the Cowlitz and Skookumchuck Formations (Vine, 1969; Johnson and others, 1997) in the Centralia-Chehalis coal field (fig. 2). The coal-bearing strata accumulated in intertidal and deltaic environments along a tidal-influenced delta plain (Brownfield and others, 1994, 2005; Flores and Johnson, 1995).

The marginal marine Spencer Formation and the marginal marine and deltaic Coaledo Formation (fig. 8) (Beaulieu, 1971) may be equivalent, in part, to the middle Eocene to Oligocene Clarno Formation (Brownfield, 2008) and the “Herren formation” of Shorey (1976). The upper Eocene Spencer contains lignite, coal, and carbonaceous shale in the upper parts of the unit (Beaulieu, 1971). The middle to upper Eocene Coaledo Formation in the Coos Bay coal field (fig. 2) contains numerous coal beds (Brownfield, 1981). The upper middle Eocene Tyee Formation (fig. 5) in the southern part of Coos County, Oreg. (fig. 1), southeast of the Coos Bay coal field, contains coal beds in the Eden Ridge coal field (fig. 2) (Brownfield, 1981) and may be equivalent, in part, to the Clarno Formation (Beaulieu, 1971).

An events chart (fig. 60) for the Cretaceous-Tertiary Composite TPS graphically portrays the ages of source, seal, and reservoir rocks, as well as the timing of trap development and generation, migration, accumulation, and preservation of hydrocarbons.

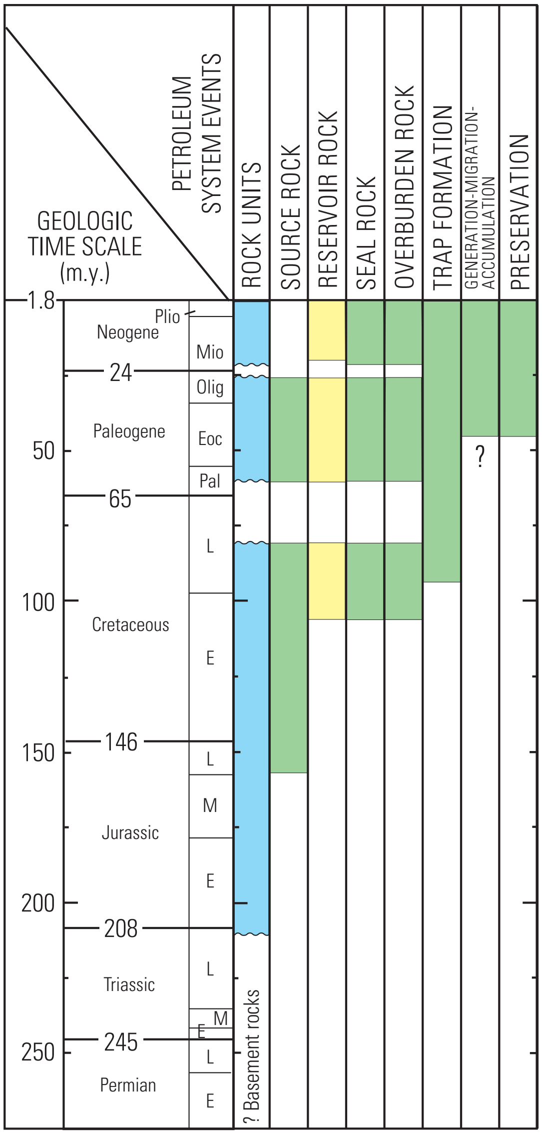

Figure 60. Events chart for the Cretaceous-Tertiary Composite Total Petroleum System in the Western Oregon and Washington Province. The petroleum system was first defined during the assessment of the Eastern Oregon and Washington Province (Brownfield, 2008). Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the time of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Modified after Brownfield (2008) to include the possible source rocks in the Upper Jurassic to Lower Cretaceous Myrtle Group and the Upper Jurassic to Lower Cretaceous Dothan Formation of southern Oregon. Geologic time scale in millions of years (m.y.). Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; M, Middle; E, Early.

Hydrocarbon source rocks include lacustrine shales in the Eocene Swauk and Chumstick Formations and coals in the Eocene Manastash, Naches, and Roslyn Formations within the eastern Washington part of the TPS (Brownfield, 2008). In the western Washington part of the TPS, the source rocks include the coal- and carbonaceous-shale-bearing Eocene Chuckanut, Huntingdon, Renton, Tiger Mountain, Spiketon, Carbonado, Skookumchuck, and Cowlitz Formations and the undivided Eocene Puget Group (fig. 5).

In the Bellingham Basin, the coal zone in Chuckanut and Huntingdon Formations was penetrated at depths ranging from 1,700 to 3,700 ft in several exploration wells (fig. 38). In the Birch Bay No. 1 well (fig. 61), coals and shales above 6,000 ft contain both Type-III and Type-IIB kerogens (Hurst, 1991; Lingley and von der Dick, 1991; Johnson and others, 1997) and several zones contain more than 6 percent total organic carbon (TOC). Rocks below 6,000 ft have Type-III kerogens and lower TOC values. Vitrinite reflectance (R_O) values ranging from 0.5 to 0.6 percent have been reported from depths of 1,700 to 7,600 ft in the Bellingham Basin, and in outcrops of the Chuckanut Formation on the southern part of the basin R_O is 0.74 percent (fig. 61). Porosity values in the Chuckanut Formation arkosic sandstones in the Birch Bay No. 1 well decreases from 26 percent at a depth of 1,000 ft to less than 10 percent at a depth of 6,000 ft (Hurst, 1991), and measured permeabilities range from less that 1 millidarcy (mD) to 58 mD (Johnson and others, 1997). Good reservoir rocks are present in the well to a depth of 4,500 ft. The decrease in reservoir quality with depth is the result of diagenetic alteration of feldspars and lithic rock fragments.

The undifferentiated middle to upper Eocene Puget Group and the Tiger Mountain, Renton, Spiketon, and Carbonado Formations of the Puget contain coal and carbonaceous mudstone source rocks with R_O values ranging from about 0.35 to 2.0 percent (Walsh and Lingley, 1991). The underlying Raging River Formation (fig. 5) contains possible marine mudstone (Vine, 1969; Johnson and O'Connor, 1994) with total organic carbon (TOC) contents ranging from 0.8 to 1.1 weight percent and R_O values ranging from 1.18 to 4.01 percent (fig. 62). These rocks crop out only at Tiger Mountain (figs. 41 and 62) and are inferred to underlie a major portion of the Puget Lowland (Stanley and others, 1992; Johnson and Stanley, 1995; Johnson and Tennyson, 1995; Johnson and others, 1997). Johnson and O'Connor (1994) reported that, although in the Tiger Mountain area these rocks are overmature, they may exist at depth to the west and generated hydrocarbons in the past. Enhanced maturation may have occurred adjacent to Eocene and younger intrusive centers that lie within or on the margins of the Puget Lowland (Esposito and Whitney, 1995).

Reservoir rocks include fluvial and distributary-channel sandstones in the middle to upper Eocene Tiger Mountain, Renton, Carbonado, and Spiketon Formations and undifferentiated Puget Group (Buckovic, 1979). Individual sandstone beds range in thickness from 10 ft to more than 200 ft and are bounded by flood-plain deposits including coal and

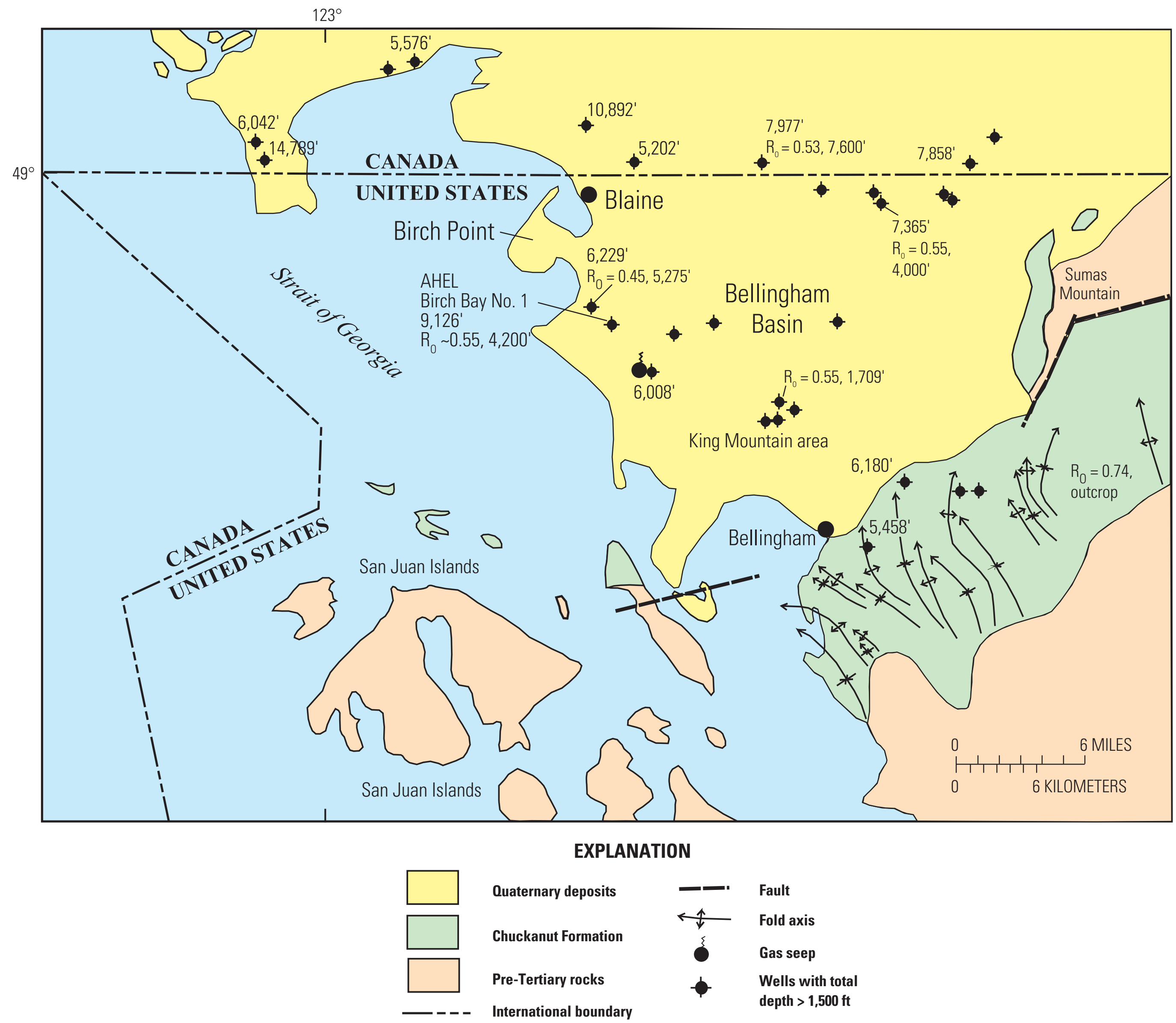

Figure 61. Map showing geology and locations of exploration wells for the Bellingham Basin area, northwestern Washington. Petroleum wells in the United States are listed in McFarland (1983) or in addendum to McFarland available through the Washington Division of Geology and Earth Resources. Petroleum wells in Canada are listed in Mustard and Rouse (1994). Thermal maturity data (R_0, mean vitrinite reflectance) are from Hurst (1991) and Walsh and Lingley (1991); values are from surface samples unless footage from adjacent well is listed. Modified after Johnson and others (1997).

carbonaceous mudstone (Vine, 1969; Johnson and Stanley, 1995). Sandstone reservoirs might be present at depths of as much as 10,000 ft (Johnson and O'Connor, 1994; Johnson and others, 1997). The reservoir sandstones are generally arkosic but contain lithic rock fragments that contribute to the loss of porosity due to alteration and compaction at depth.

North of Morton, Wash. (fig. 62), the middle Eocene Carbonado Formation (fig. 5) is about 3,900 ft thick and consists of nonmarine and shallow-marine rocks deposited within a tide-influenced delta. Potential gas-prone source rocks are shallow-marine mudstones, coals, and carbonaceous shales. Samples analyzed from a coal exploration borehole (fig. 62; Amoco WC-83-5) north of Morton, Wash., show R_O values ranging from 0.96 to 1.69 percent (Johnson and Stanley, 1995). Potential reservoir rocks in the Carbonado Formation consist of fine- to coarse-grained sandstone beds of fluvial origin and generally range in thickness from 15 to 65 ft but can be as much as 230 ft thick. No porosity and permeability data

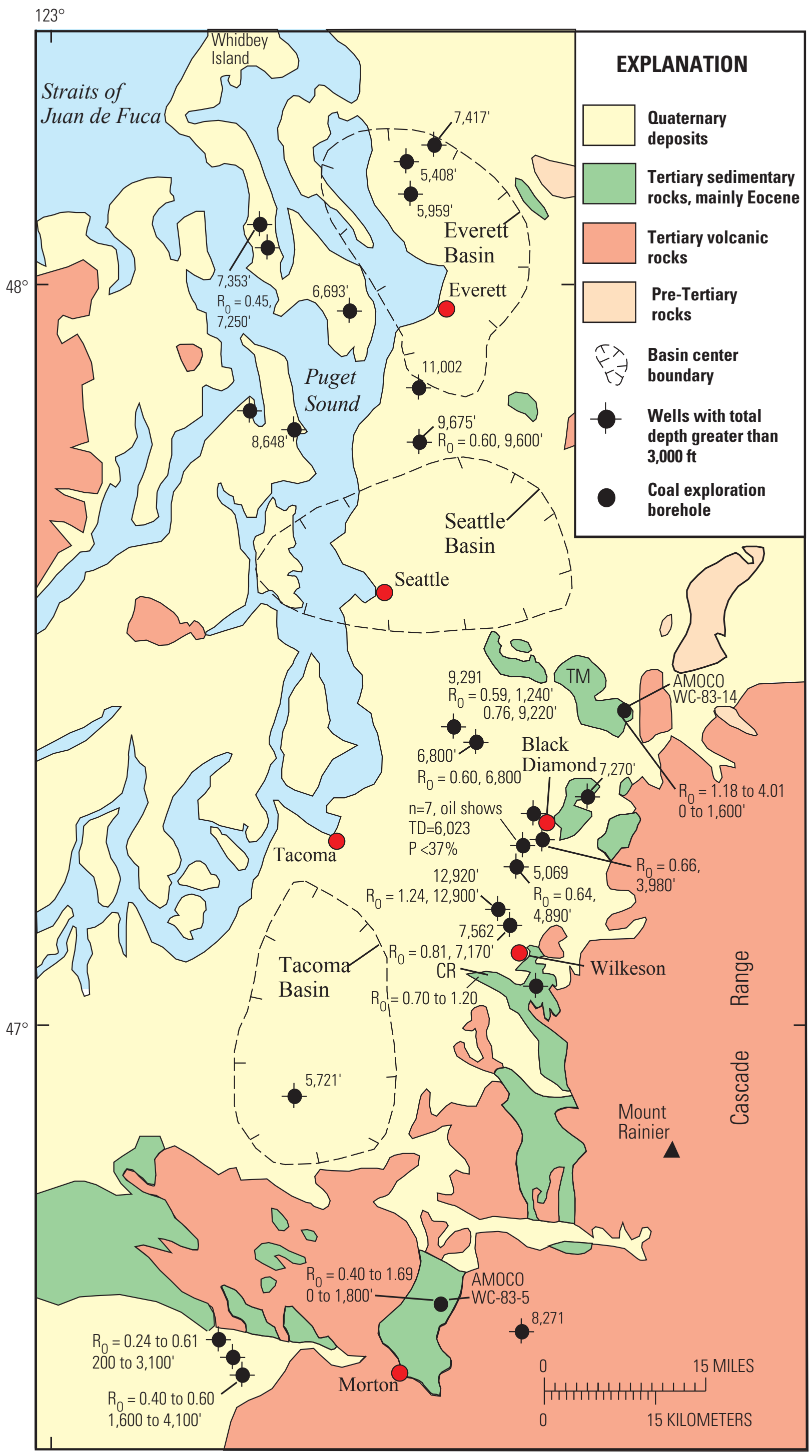

Figure 62. Map showing geology and locations of exploration wells for the Puget Lowland, northwestern Washington. Petroleum wells are listed in McFarland (1983) or in addendum to McFarland available through the Washington Division of Geology and Earth Resources. Thermal maturity data (R_0, mean vitrinite reflectance) are from Walsh and Lingley (1991), Johnson and O'Connor (1994), Johnson and Stanley (1995), and Johnson and others (1997); values are from surface samples unless footage from adjacent well is listed. CR, Carbon River area; TM, Tiger Mountain. Modified after Walsh and others (1987) and Johnson and others (1997).

are available, but outcrop samples are typically well cemented (Johnson and Stanley, 1995).

The middle to upper Eocene marine mudstone of the McIntosh Formation and shallow-marine to deltaic mudstone and coal and carbonaceous shale of the Skookumchuck and Cowlitz Formations are potential source rocks in the Chehalis Basin and the eastern part of the Grays Harbor Basin (fig. 63). These source rocks include marine shale, coals, and carbonaceous mudstones (Snavely and others, 1958; Armentrout and Suek, 1985; Moothart, 1992; Niem and others, 1994; Brownfield and others, 1994; Flores and Johnson, 1995). The organic matter is Type III and is gas prone. Marine mudstones west of Centralia, Wash. (fig. 63), have total organic carbon (TOC) values ranging from 0.5 to 1.25 percent and vitrinite reflectance (R_O) values ranging from 0.4 to 0.5 percent (Moothart, 1992). Armentrout and Suek (1985) reported that Skookumchuck Formation siltstone samples have TOC values ranging from 1.35 to 7.22 percent and coal samples have TOC values from 39.23 to 55.19 percent. Coals in the Skookumchuck and Cowlitz Formations were sampled from the surface to a depth of 10,000 ft; they range from lignite to subbituminous rank with R_O values ranging from about 0.35 to 0.6 percent but can be slightly higher (fig. 63). Walsh and Lingley (1991) reported R_O values ranging from 0.4 to 0.87 percent from samples collected from two wells (depth 4,080 and 9,540 ft, respectively) in the Chehalis Basin. Thermal maturity generally increases to the east and in close proximity to intrusives (Esposito and Whitney, 1995). Reservoir rocks include middle to upper Eocene fluvial- and distributary-channel arkosic sandstones of the Cowlitz and Skookumchuck Formations, and marine sandstones of the McIntosh Formation. The sandstone reservoirs are as thick as 170 ft and generally arkosic (Henricksen, 1956; Snavely and others, 1958; Wurden and Ford, 1976; Brownfield and others, 1994; Flores and Johnson, 1995). Wurden and Ford (1976) reported than Skookumchuck Formation sandstones in the Jackson Prairie gas storage wells (fig. 63) have porosities ranging from 28 to 40 percent at depths of 1,500 to 3,000 ft and permeabilities as high as 8,500 mD. The Skookumchuck sandstones are comparable to those reported from the Mist field of northwestern Oregon where gas is produced from Cowlitz Formation sandstones.

Interpretation of seismic data indicate the presence of possible marine strata at depths of 6,500–16,400 ft below the Chehalis Basin and north of Morton, Wash. (figs. 62 and 63), providing another possible source rock (Stanley and others, 1994; Stanley and others, 1996; Krehbiel, 1993; Johnson and Stanley, 1995). Enhanced maturation of source rocks has occurred adjacent to intrusive centers within or on the margins of the AU area.

In the western Oregon part of the Cretaceous-Tertiary Composite TPS, potential source rocks are organic-rich mudstones and coal facies of the Eocene Umpqua Group and Tyee, Coaledo, Yamhill, Cowlitz, and Spencer Formations (fig. 8). Mudstone in the underlying pre-Tertiary melange terrane in the Klamath Mountains may be source rocks (Law and others, 1984; Ryu and others, 1996; Ryu, 2008), with total organic carbon values greater than 1 percent (Ryu and others, 1996).

In the southern part of the Oregon Coast Range, potential source rocks in the Umpqua Group include carbonaceous mudstone or coal in the White Tail Ridge Formation and possibly mudstones in the Tenmile Formation (Niem and Niem, 1990; Ryu and others, 1996; Ryu, 2008), although mudstones in the Tenmile Formation contain TOC values less than 1 percent.

Source rocks in the Tyee Formation include coals and carbonaceous mudstones in the Baughman Member, with TOC values as much as 43 percent (Law and others, 1984). Niem and Niem (1990) reported that Tyee Formation coals and carbonaceous shales in the Eden Ridge coal field (fig. 2) contain TOC values of more than 50 percent and sufficient volatile organic matter (28 to 58 percent) to generate gas. The Tyee Mountain and Baughman Members of the Tyee Formation contain organic-rich mudstones ranging from less than 1 percent to about 2.5 percent TOC (Ryu and others, 1996). Organic matter is dominantly gas-prone Type III. The Eocene sequence is generally marginally mature for oil and immature for gas, as measured in surface samples, in which R_O values are generally in the range of 0.5 to 0.8 percent (Law and others, 1984; Niem and Niem, 1990; Ryu and others, 1996; Ryu, 2008). Subsurface samples from five wells in the southern Oregon Coast Range have typical R_O values of 0.45–0.66 percent (Niem and Niem, 1990; Ryu and others, 1996).

Modeling of burial history, thermal maturity, and timing of hydrocarbons was reconstructed for the Tyee forarc basin (fig. 13) using 45 measured sections and 11 oil and gas exploration wells (Ryu and others, 1996). Table 1 lists the 13 oil and gas wells in the Roseburg quadrangle with depths up to 13,177 ft; see figure 9 for the locations of the wells (Wells and others, 2000). The model indicates that rapid deposition and burial of sediment probably began in the early Eocene with a short period of uplift in the latest Eocene (fig. 64). This uplift was followed by renewed subsidence during deposition of the Coos Bay Basin strata. During the middle Miocene, the southern Oregon Coast Range began a rapid uplift that slowed during the Pliocene and Pleistocene but continues today (Niem and others, 1992). The maturity model by Ryu and others (1996) indicates that (1) the lower part of the Umpqua Group could have entered the hydrocarbon generation window during the middle Eocene; and (2) the Tenmile Formation entered the generation window in the late Eocene, and at present the lower Umpqua and Tenmile have reached moderate levels of maturity (>0.07 R_O percent). Also, at the present time, the White Tail Ridge and Camas Valley Formations of the Umpqua Group are within the generation window at depths ranging from 8,500 to 14,500 ft. However, source rocks in the overlying Tyee, Elkton, and Bateman Formations have not been buried deep enough to generate hydrocarbons.

Gas seeps (mainly biogenic) and two oil seeps (Niem and Niem, 1990) indicate the likely presence of mature source rocks within the Western Oregon and Washington Province; the oil seeps may be derived from sources in Mesozoic

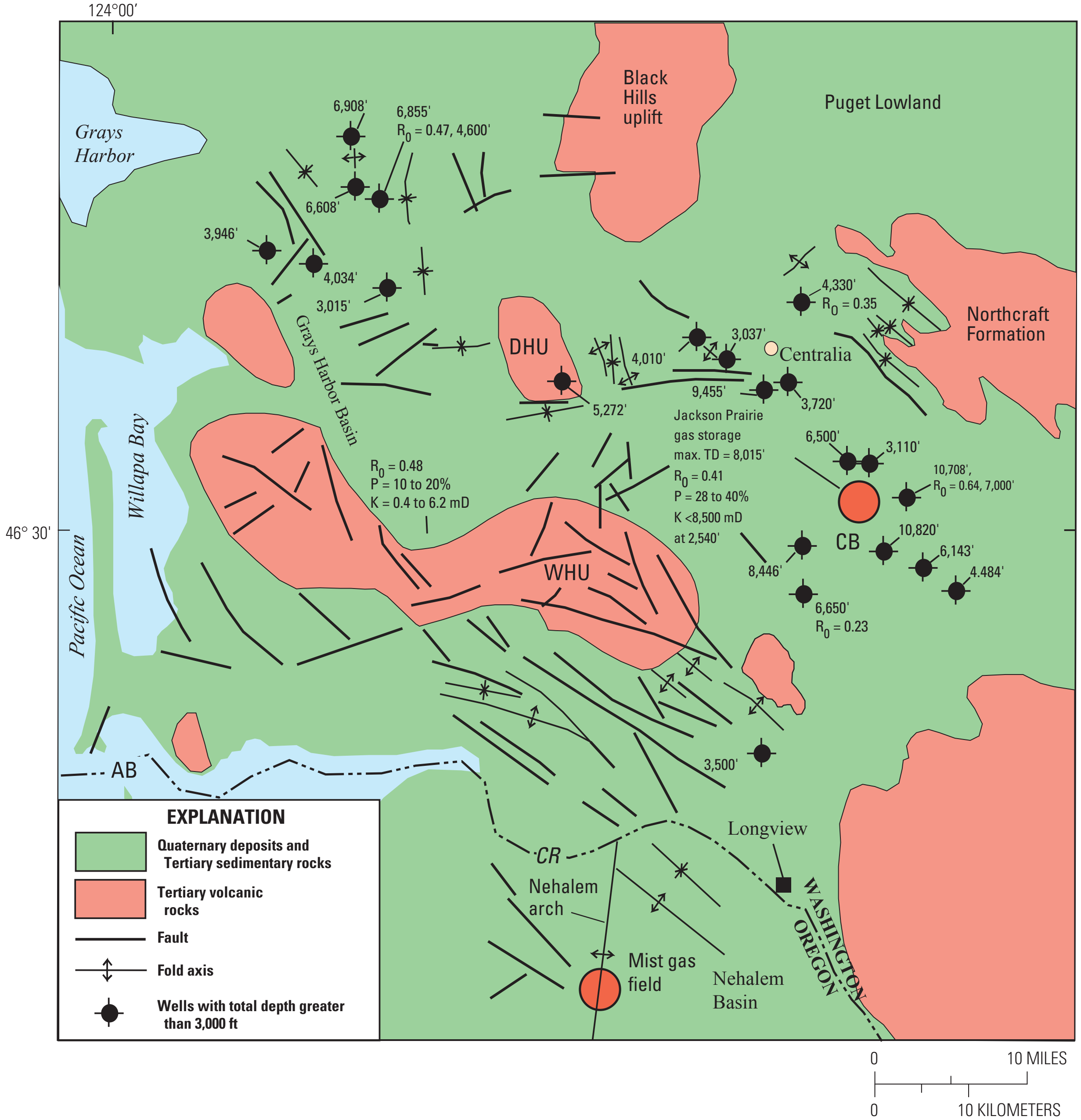

Figure 63. Map showing the geology and locations of exploration wells for the southern part of the Puget Lowland and the Centralia and Grays Harbor Basins, southwestern Washington. Geology (including selectively displayed faults and folds) is based on Wells (1981), Walsh and others (1987), and Walker and MacLeod (1991). Petroleum wells in Washington are listed in McFarland (1983) or in addendum to McFarland available through the Washington Division of Geology and Earth Resources. Thermal maturity data (R_0, mean vitrinite reflectance), porosity (P), and permeability (K, in millidarcies, mD) are from Wurden and Ford (1976), Walsh and Lingley (1991), Moothart (1992), or Johnson and others (1997); values are from surface samples unless footage from adjacent petroleum well is listed. AB, Astoria Basin; CB, Chehalis Basin; DHU, Doty Hills uplift; WHU, Willapa Hills uplift. Modified after Johnson and others (1997).

Table 1. Oil and gas exploration wells in the Roseburg 30 x 60 quadrangle, Douglas and Coos Counties, Oregon. See figure 9 for location of wells.

[Well number from Niem and Niem (1990); well depth in feet]

Well number	Well name	Well depth	Latitude	Longitude
4	Amoco Weyerhaeuser F-1	4,428	43.406	123.837
5	Amoco Weyerhaeuser B-1	11,330	43.386	123.714
6	Sheldon C. Clark “Oakland well”	2,235	43.405	123.311
7	Mobil Oil Corp. Sutherlin Unit 1	13,177	43.434	123.238
8	Union Oil Co. Liles 1	7,002	43.362	123.506
9	Hutchins & Marrs Glory Hole 1	2,987	43.238	123.521
10	Community Oil & Gas Co. Scott 1	3,693	43.242	123.440
11	Diamond Drill Contracting Co. Hamilton Ranch Well 3	545	43.246	123.511
12	Diamond Drill Contracting Co. Hamilton Ranch Well 1	628	43.182	123.553
13	Diamond Drill Contracting Co. Hamilton Ranch Well 2	1,109	43.221	123.515
14	W. F. Kernin Well 1	3,900	43.217	123.417
14	F. W. Dillard unnamed	700	43.176	123.474
16	Uranium Oil & Gas Co. Ziedrich 1	4,368	43.051	123.657

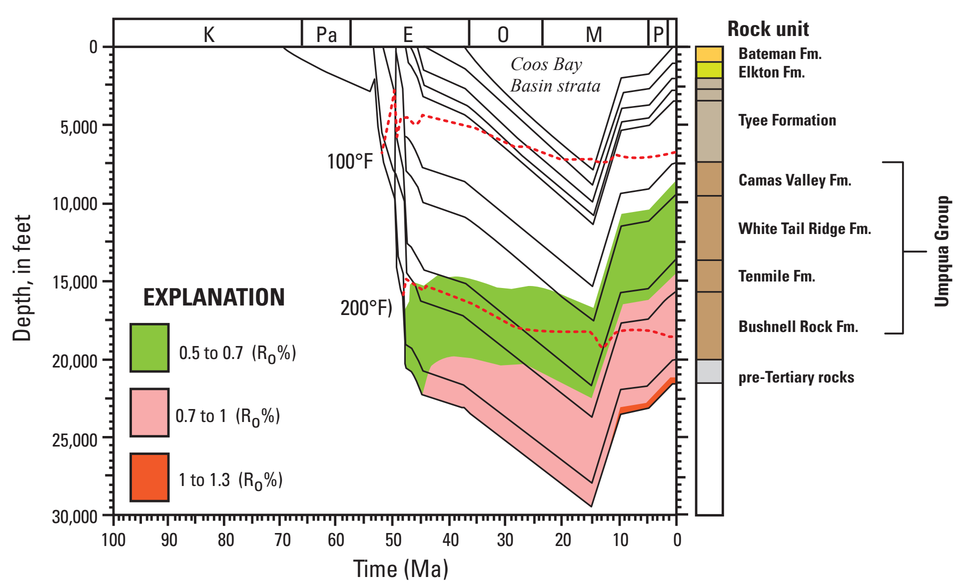

Figure 64. Burial history model for strata in the Tyee Basin using a composite section modified after Ryu and others (1992). Red dashed line represents time-temperature index curve. Formation thicknesses are from Ryu and others (1992). Thermal history is calculated using a steady state heat flow of 1.27°F per 100 ft. Maturity was derived from Lawrence Livermore National Laboratories Easy Percent R_0. Time interval for calculation of maturity and expulsion is five. Expulsion is based on vitrinite reflectance (R_0). K, Cretaceous; Pa, Paleocene; E, Eocene; O, Oligocene; M, Miocene; P, Pliocene.

mudstones in the Klamath melange terranes, including the Myrtle Group and Dothan Formation. These units probably are below the Umpqua Group and Tyee Formation in the southernmost part of the Roseburg quadrangle (fig. 9). Biogenic gas seeps in deltaic facies of the White Tail Ridge Formation of the Umpqua Group west of Roseburg, Oreg. (fig. 9), appear to be sourced by interbedded coal and carbonaceous mudstones (Ryu and others, 1996).

Potential source rocks in the Coaledo Formation (fig. 8) include coal and mudstone interbedded with potential reservoir sandstones. Total organic carbon (TOC) in the Coaledo Formation mudstone is about 1.45 percent, according to Law and others (1984). The Umpqua Group and Tyee and Elkton Formations contain TOC values ranging from 0.4 percent to 1.35 percent with one Tyee coal containing 36.61 percent TOC (Law and others, 1984). These units are all thermally immature for gas as indicated by outcrop samples, for which analyses show R_O values between 0.32 percent and 0.61 percent (Newton, 1980; Law and others, 1984). Numerous gas and oil shows in exploration and water wells in the Coos Bay area indicate that an unidentified mature source is probably present; gas from the Pacific Petroleum Morrison No. 1 well contains 0.15 percent “heavy fraction” (Olmstead, 1989) suggesting a thermogenic origin for some of the gas.

In west-central and northwestern Oregon, source rocks are mudstone or coal facies of the Tyee, Yamhill, Cowlitz, and Spencer Formations (figs. 6 and 8). Potential lean gas-prone mudstone source rocks may locally be in the Tyee Formation in the central Oregon Coast Range, but no data were available for this assessment. Locally thin, kerogen-rich, immature (R_O of 0.3 percent) laminated “oil shales” are interbedded in the middle to upper part of the Yamhill Formation in the Tillamook Highlands near Tillamook, Oreg. (fig. 6) (Snavely and others, 1993a); the Yamhill Formation ranges in thickness from 490 to 820 ft. Eight beds, as much as 4 in. thick, were mapped and one analyzed sample contained 2.14 percent total organic carbon. The main kerogen-bearing section consists of feldspathic basaltic sandstone, siltstone, and lapilli tuff in the upper part of the section. These kerogen-rich beds may represent a condensed section deposited in a restricted marine-shelf basin in structural lows interbedded with upper middle Eocene volcanics. Similar kerogen-rich beds crop out north of the Columbia River in southwestern Washington (Wolfe and McKee, 1968) and north of Grays Harbor (fig. 54) (Rau, 1986).

Marine shale and thin coals and carbonaceous shale of the middle to upper Eocene Cowlitz Formation are the inferred source rocks (Armentrout and Suek, 1985; Niem and others, 1994) for undiscovered accumulations in the northwestern part of Oregon. Organic matter in these rocks is Type-III kerogen and is gas prone. Coals are of lignite to subbituminous rank; R_O is generally between 0.35 and 0.6 but can be slightly higher. R_O of marine mudstone at the surface and shallow (<5,000 ft) subsurface is generally 0.4 to 0.5, with typical TOC values of 0.5 to 1.25 weight percent.

In the Mist gas field area (fig. 1), analyzed surface samples of mudstone from the Cowlitz Formation yield total organic carbon (TOC) values ranging from 0.39 to 1.07 weight percent (Armentrout and Suek, 1985) and average 0.68 percent, whereas subsurface samples of potential source rocks in the Mist gas field are lean with vitrinite reflectance (R_O) values averaging 0.21 percent. The data indicate that the gas probably was not generated in place and must have migrated from zones of higher maturity. The arkosic sandstones of the Cowlitz Formation have porosities ranging from 14 to 41 percent, averaging 25 percent, and permeabilities ranging from 46 to 1,500 millidarcies (mD) with an average of 200 mD (Armentrout and Suek, 1985). These sandstones are less susceptible to diagenetic alteration than the more lithic-bearing sandstones. Samples of the upper Eocene and Oligocene Keasey Formation (fig. 8) above the Cowlitz contain 0.18 to 0.91 percent TOC and R_O values ranging from 0.16 to 0.31 percent (Law and others, 1984; Armentrout and Suek, 1985).

The upper Eocene Spencer Formation (fig. 8) contains potential source rocks consisting of coals and carbonaceous mudstone that correlate to the productive zones of the Cowlitz Formation in the Mist gas field (Van Atta and Thoms, 1993). Law and others (1984) reported that the Spencer Formation in the southern part of the Willamette Valley contains 4.48 weight percent TOC and an R_O value of 0.48 percent. Potential reservoir rocks in the Spencer Formation include arkosic sandstone beds ranging in thickness from 2 to 30 ft and have a cumulative thickness of about 200 ft (Schlicker, 1962). Analyzed samples contain porosity values ranging from 32.2 to 41.5 percent and permeability values ranging from 184 to 4,510 mD. Van Atta and Thoms (1993) reported a clean arkosic sandstone about 980 ft thick in the Humble Oil Miller No. 1 well about 70 mi south of Portland, Oreg., near Albany, Oreg. There was one gas discovery in the Spencer Formation in 1981 at the American Quasar Hickey 9-12 well in Linn County southwest of Portland, Oreg. (fig. 1) (Olmstead, 1989). Production continued for about five months and was then abandoned because the volume of gas became subcommercial.

Before 1979, the only conventional oil and gas production in the Western Oregon and Washington Province was in Washington: (1) in Whatcom County, near Bellingham, Wash. (fig. 61), where small amounts of gas were produced from the Chuckanut Formation below Quaternary gravels; and (2) west of Aberdeen, Wash. (fig. 54), where about 12,000 barrels of oil and associated gas were produced from 1957 to 1961. Currently, the only hydrocarbon production is from the Mist gas field in northwestern Oregon (fig. 1), which was discovered in May 1979 (Bruer, 1980). Through 2008, the field has produced about 65 BCFG from sandstone reservoirs in the Cowlitz Formation.

The abandoned Rattlesnake Hills gas field (Hammer, 1934), southwest of Yakima, Wash., is in the eastern part of the Cretaceous-Tertiary Composite TPS (figs. 1 and 2). This field was discovered in 1913 and produced about 1.3 BCFG before it was abandoned in 1941 (McFarland, 1979). Production was from two vesicular basalt zones sealed by sedimentary interbeds less than 2,000 ft deep within the Columbia River Basalt Group. The gas probably was generated from the underlying Eocene coals (Johnson and others, 1993) and was mostly methane with about 10 percent nitrogen (Wagner, 1966). Johnson and others (1993) reported that the gas in the basalt aquifers was thermogenic.

Tertiary Marine Total Petroleum System (500402)

A second total petroleum system (TPS)—the Tertiary Marine TPS—is defined within the northwestern part of the Western Oregon and Washington Province (fig. 1). The TPS boundary is defined on the basis of where potential Tertiary marine and marginal-marine reservoirs and gas-prone source rocks are known to exist or inferred to exist. The TPS boundary includes the Tofino-Fuca Basin Gas, Western Washington Melange, Southwest Washington Miocene Sandstone, and the Astoria plays of Johnson and Tennyson (1995) and Johnson and others (1997).

In the northern part of the Tertiary Marine TPS, more than 28,000 ft of north-dipping Eocene to lower Miocene strata contain gas-prone source rocks (Niem and Snavely, 1991). These source rocks are deeply buried Eocene marine mudstones in the offshore part of the Tofino-Juan de Fuca Basin (fig. 65) that contain Type-III kerogen and 0.3 to 1.2 percent TOC (Snavely and others, 1980; Niem and Snavely, 1991). A second potential source rock is marine mudstones in Eocene to Oligocene Ozette terrane and other melange units (fig. 5) (Snavely and Kvenvolden, 1989) containing Type-III kerogen and 0.4 to 0.9 weight percent TOC. The Eocene melange units, which crop out in the Olympic Peninsula (figs. 46 and 65), lie beneath the Crescent thrust fault (Niem and Snavely, 1991) with the Eocene Crescent Formation and other Eocene strata in the overriding block (figs. 48 and 65). Vitrinite reflectance values range from 0.4 to 0.5 percent from surface and well samples (Snavely and others, 1980; Niem and Snavely, 1991). Higher thermal maturity is expected where these rocks are buried as deep as 25,000 ft to the north in the deeper parts of the Tofino-Juan de Fuca Basin. The upper Eocene to lower Miocene turbidite sandstones of the Twin River Group (fig. 5) are potential reservoir rocks (Snavely and others, 1980; Niem and Snavely, 1991), the best of which have porosities ranging from 20.4 to 24.6 percent and permeabilities ranging from 2 to 657 mD (Niem and Snavely, 1991).

Eocene to Oligocene Ozette terrane and Oligocene to middle Miocene Hoh rock assemblage (fig. 5) mudstones are possible source rocks and are inferred to exist through much of the western part of the TPS (figs. 50, 51, and 66). The Ozette and Hoh rocks contain 0.5 to 1.0 weight percent TOC and contain Type-III kerogen (Snavely and Kvenvolden, 1989). In the Grays Harbor area (fig. 67), the vitrinite reflectance (R_O) values are about 0.5 percent at a depth of 5,100 ft; however, about 15 miles to the north, R_O values in outcrop samples range from 0.87 to 1.98 percent (fig. 64). Snavely and Kvenvolden (1989) reported vitrinite reflectance values of about 0.6 percent for rocks at depths of 6,000 ft in the Ocean City area (fig. 67). The distribution of Ozette and Hoh source rocks has not been determined, but the Paleogene melange should extend down to the top of the subducting Juan de Fuca plate (at least 50,000 ft). Marine-turbidite channel sandstones located in coherent structural blocks of the Ozette terrane and the Hoh rock assemblage are potential reservoir rocks. Palmer and Lingley (1989) reported that sandstone units in the Grays Harbor area (fig. 1) range from 10 to 100 ft in thickness and composite sandstone units are as thick as 140 ft (Lingley, 1995). Porosities are generally less than 25 percent and permeabilities are less than 100 mD (Palmer and Lingley, 1989).

The Oligocene Smuggler Cove formation, informally named by Niem and Niem (1985), and the lower and middle Miocene Astoria Formation (fig. 5) also contain potential source rocks with Type-III kerogen and 0.65 to 2.0 weight percent TOC. The source rocks are mostly thermally immature to marginally mature, but locally they might be thermally mature where subjected to heating from Miocene basaltic intrusions of the Columbia River Group. Law and others (1984) reported that one Astoria Formation sample yielded an R_O value of 0.65 percent and a mudstone of the informal Smuggler Cove formation yielded an R_O value of 1.78 to 1.85 percent, making it thermally mature to overmature. Potential reservoirs include the marginal marine and deltaic sandstone of the Miocene Astoria and Montesano Formations (fig. 5). Palmer and Lingley (1989) reported that a 600-ft-thick Montesano Formation sandstone in the Grays Harbor area (fig. 67) averaged 28 percent porosity and 1 darcy (D) permeability. Several sandstone beds as much as 100 ft thick were encountered in drill holes penetrating the Astoria and Montesano Formations east of Aberdeen (fig. 54) indicating that potential reservoirs may exist at depth.

An oil-prone source rock yet to be determined must be present in the TPS because of the numerous oil seeps and the approximately 12,000 barrels of oil produced from the Hoh rock assemblage in one well near Ocean City, Wash., from 1957 to 1961 (fig. 66) (McFarland, 1983; Palmer and Lingley, 1989).

An events chart (fig. 68) for the Tertiary-Marine TPS graphically portrays the ages of source, seal, and reservoir rocks, as well as the timing of trap development and generation, migration, accumulation, and preservation of hydrocarbons.

Tertiary Coalbed Gas Total Petroleum System (500403)

A third total petroleum system (TPS)—the Tertiary Coalbed Gas TPS—is defined within the Western Oregon and Washington Province (fig. 1). The TPS boundary is defined on the basis of where Paleogene coal-bearing units are known

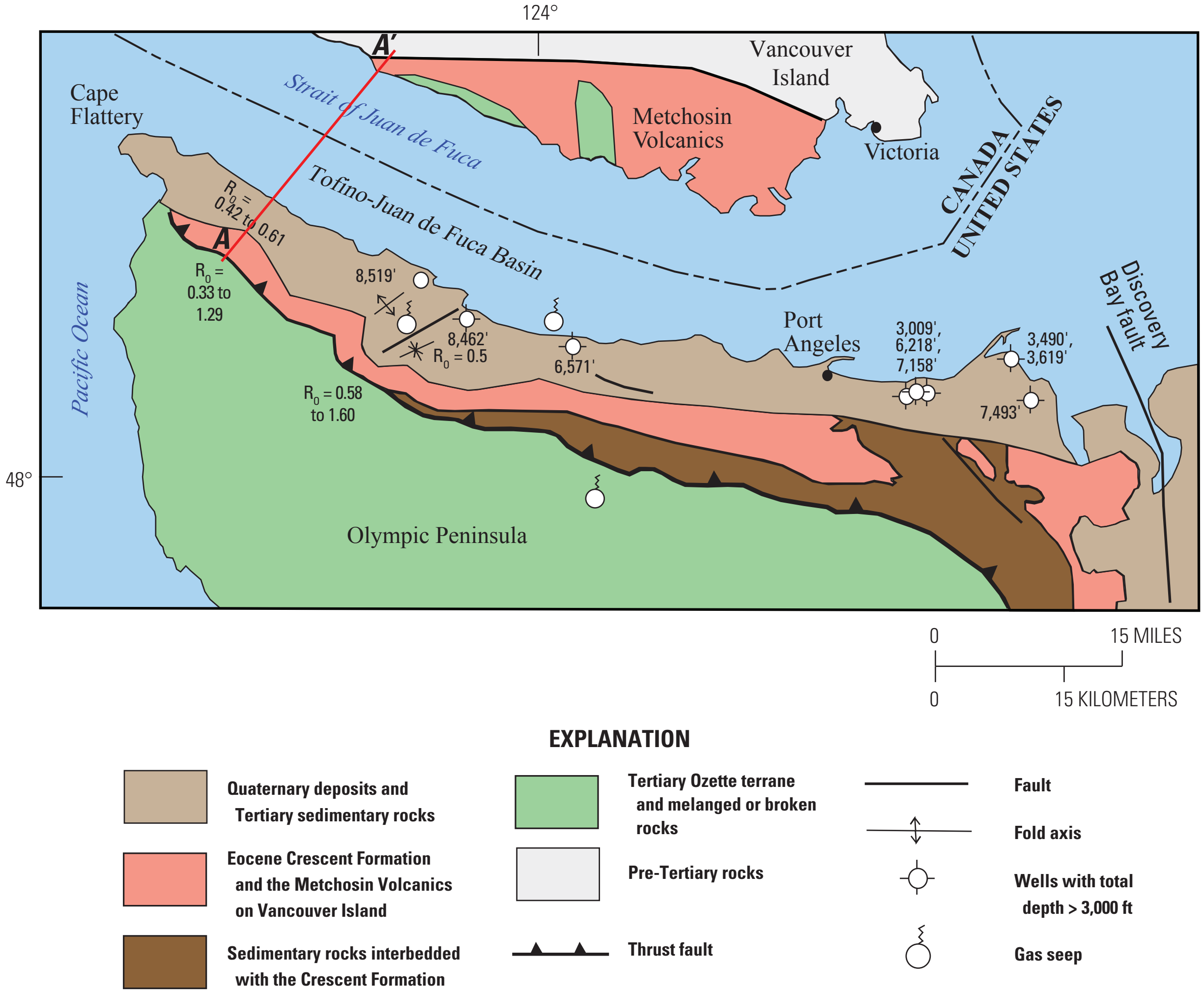

Figure 65. Map showing the generalized geology and oil and gas data for the northern part of the Olympic Peninsula, Washington, and Vancouver Island, Canada. Petroleum wells are listed in McFarland (1983) or in addendum to McFarland available through the Washington Division of Geology and Earth Resources. Geology is based on Tabor and Cady (1978a) and Niem and Snavely (1991). Thermal maturity data (R_0, mean vitrinite reflectance) and location of gas seeps are from Snavely and Kvenvolden (1989) and Niem and Snavely (1991); R_0 values are from surface samples unless footage from adjacent well is listed. Cross section *A–A′* shown in figure 48.

to exist or inferred to exist, and where the coals and carbonaceous shales are less than 6,000 ft below the surface. The coals serve as both source and reservoir rock. Coals and carbonaceous shales at depths greater than 6,000 ft were not assessed due to the potential decrease in permeability that could affect coalbed-gas recovery. Gas resource potential within the coals can be enhanced by the entrapment of migrated gas from other source rocks such as interbedded carbonaceous shale.

The Tertiary Coalbed Gas TPS likely underlies much of the central part of the Western Oregon and Washington Province (fig. 1) and extends southward from the Canadian border to the Klamath Mountains of Oregon; it contains about 11.1 million acres. The TPS includes all the Eocene coal-bearing rocks that were deposited in a regional coal-depositional system that extended north–south along depositional strike from the Bellingham area south to the Coos Bay area in southwestern Oregon (fig. 57) (Dott, 1966).

An events chart (fig. 69) for the Tertiary Coalbed Gas TPS graphically portrays the ages of source, seal, and reservoir rocks, as well as the timing of trap development and generation, migration, accumulation, and preservation of hydrocarbons.

In the Bellingham Basin (fig. 61), the Chuckanut Formation contains at least 15 coal beds ranging from 2 to about 25 ft thick with the majority of the coals in the 2- to 4-ft range; at least seven beds range from 6 to about 25 ft thick (Jenkins, 1923, 1924; Beikman and others, 1961). Two main coal zones are in Whatcom and Skagit Counties, Wash.—the

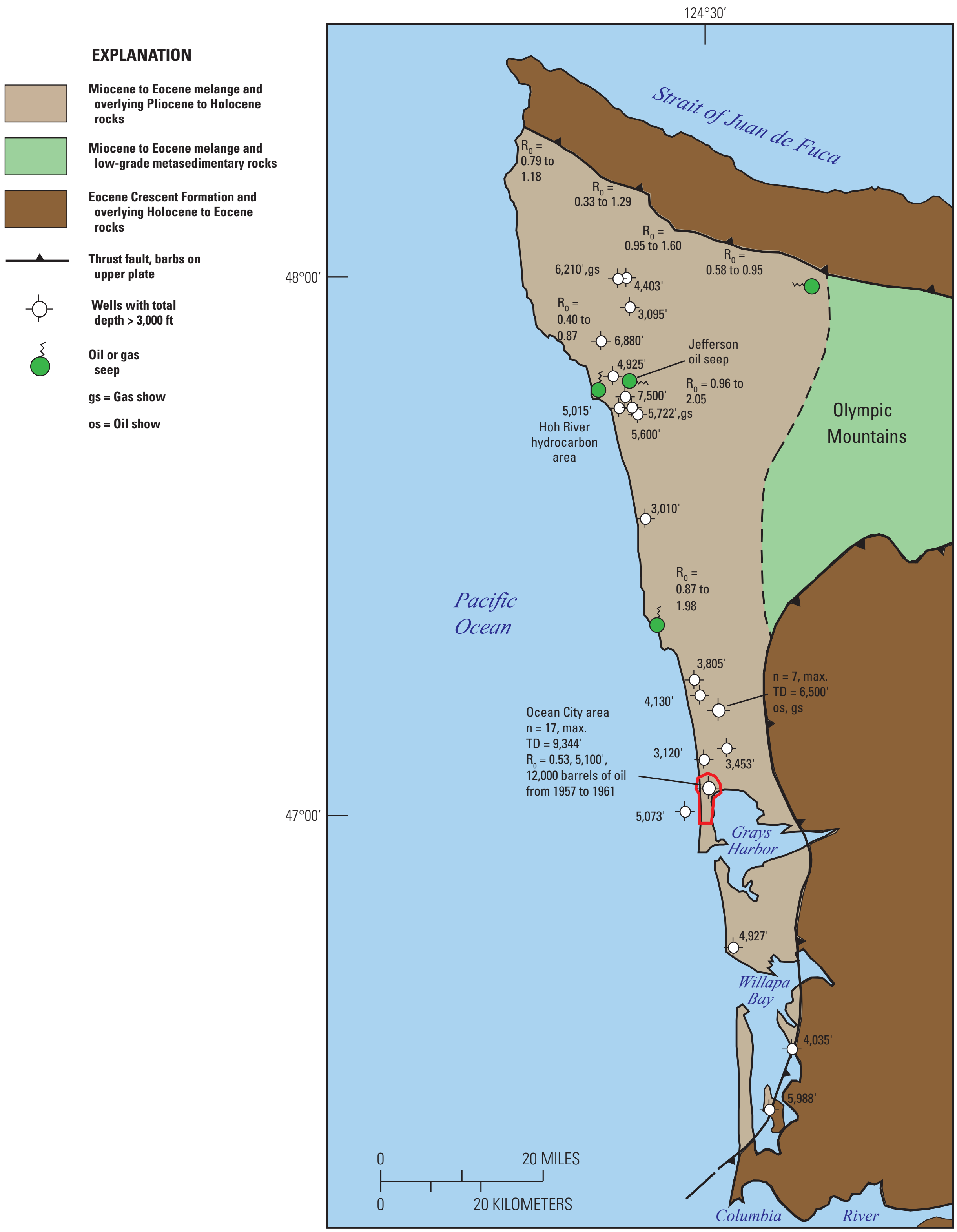

Figure 66. Map showing generalized geology and oil and gas data for northwestern Washington. Petroleum wells are listed in McFarland (1983) or in addendum to McFarland available through the Washington Division of Geology and Earth Resources. Geology is based on Tabor and Cady (1978a) and Walsh and others (1987). Thermal maturity data (R_0, mean vitrinite reflectance) and locations of seeps are from Snavely and Kvenvolden (1989) and Palmer and Lingley (1989); R_0 values are from surface samples unless footage from adjacent well is listed. Modified after Johnson and others (1997).

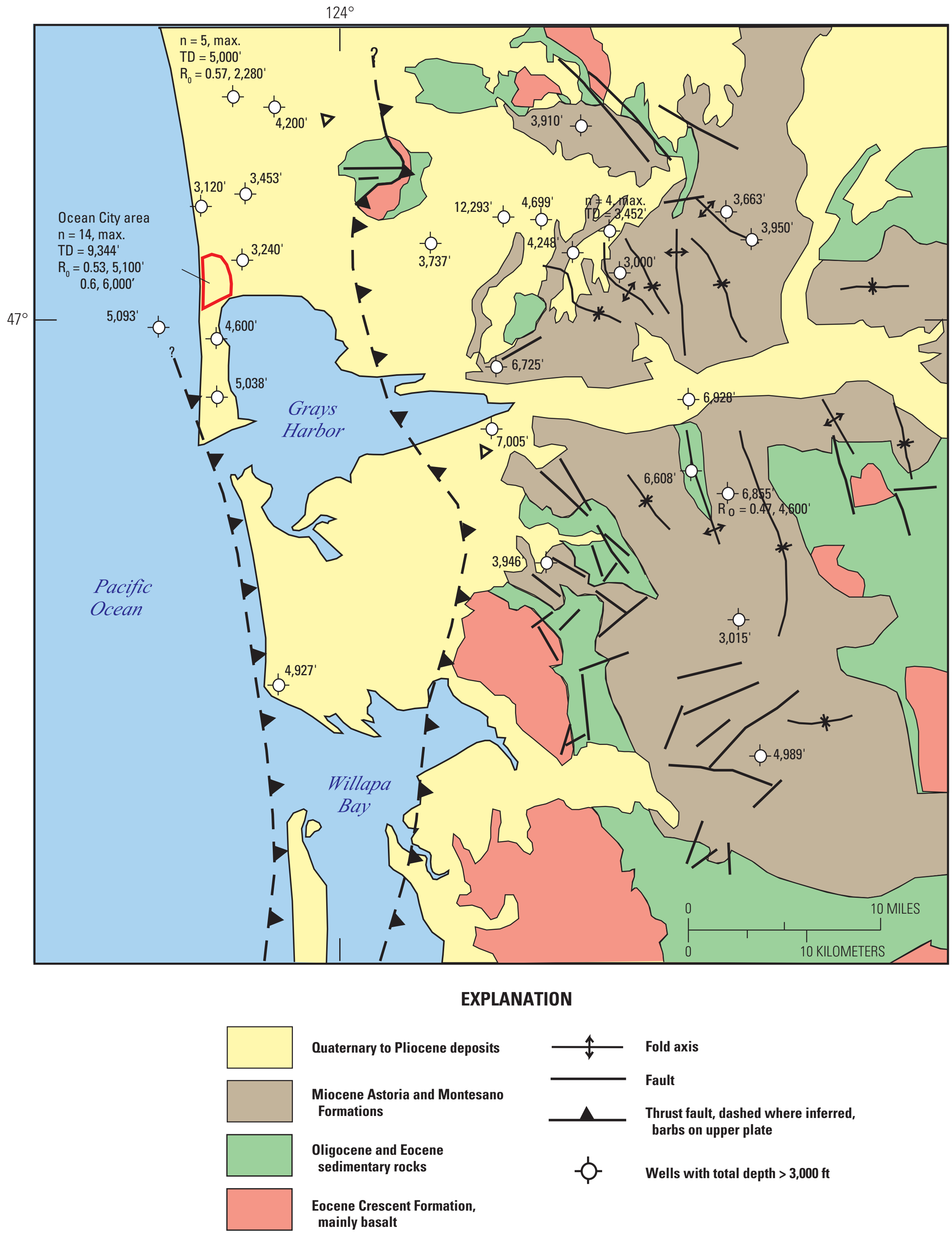

Figure 67. Map showing generalized geology and oil and gas data for southwestern Washington and the Grays Harbor area. Petroleum wells are listed in McFarland (1983) or in addendum to McFarland available through the Washington Division of Geology and Earth Resources. Geology (including selectively displayed faults and folds) is based on Snavely (1987) and Walsh and others (1987). Thermal maturity data (R_0, mean vitrinite reflectance) are from Snavely and Kvenvolden (1989) and Palmer and Lingley (1989); R_0 values are from surface samples unless footage from adjacent petroleum well is listed. Modified after Johnson and others (1997).

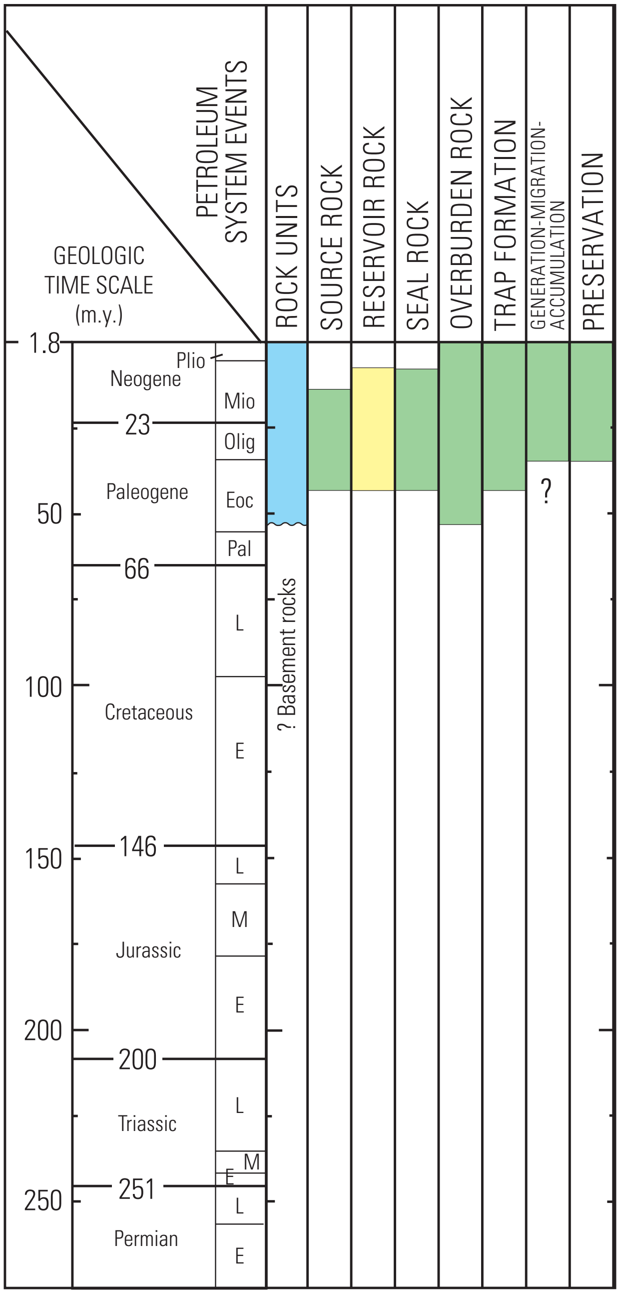

Figure 68. Events chart for the Tertiary-Marine Total Petroleum System in the Western Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the time of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Geologic time scale in millions of years (m.y.). Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; M, Middle; E, Early.

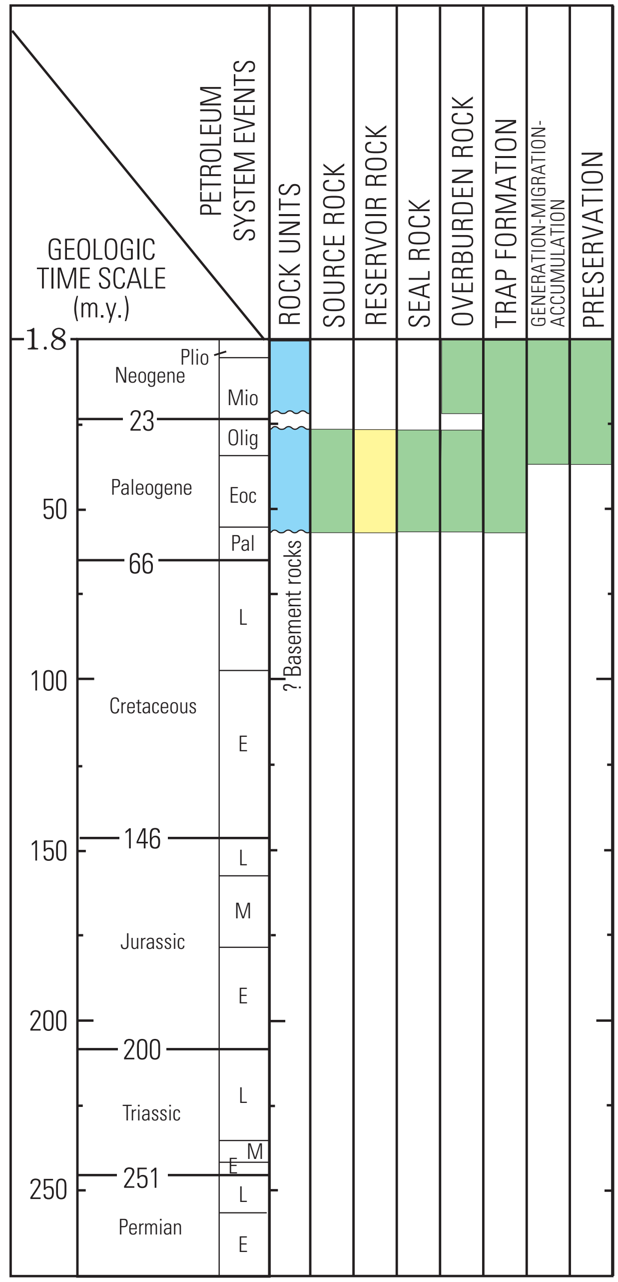

Figure 69. Events chart for the Tertiary Coalbed Gas Total Petroleum System in the Western Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the time of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Geologic time scale in millions of years (m.y.). Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; M, Middle; E, Early.

Blue canyon coal zone at the base of the Chuckanut Formation and the Bellingham coal zone of the Chuckanut Formation (also known as the King Mountain coal zone). The Bellingham Basin coal beds, which crop out along the western flank of the Cascade Range, from Bellingham to the town of Glacier (fig. 3), are lenticular and range in apparent rank from subbituminous to anthracite; however, most of the coals are high-volatile C to B bituminous in apparent rank. Jordan Exploration Company (2002) reported individual coal beds ranging from 1 to 16 ft thick with at least seven beds from 6 to 16 ft thick and a potential aggregate coal thickness of more than 90 ft. Historical mining reports stated that the coals were gassy. An increase in apparent rank to as high as anthracite can be observed from west to east with increasing proximity to the areas of higher heat flow associated with the Cascade Range volcanism (Walsh and Lingley, 1991).

The King Mountain coal zone identified in the subsurface north of Bellingham most likely correlates to the Bellingham Bay Member of the Chuckanut Formation (Johnson and others, 1997). This coal zone contains as many as eight coal beds averaging 5 ft thick, with no beds greater than 10 ft thick. The coal zone was penetrated at depths ranging from 1,700 to 3,700 ft in several exploration wells. In the Birch Bay No. 1 well (fig. 61), shales, carbonaceous shales, and coals above 6,000 ft contain both Type-III and Type-IIB kerogens (Hurst, 1991; Lingley and von der Dick, 1991; Johnson and others, 1997), and several zones contain more than 6 percent total organic carbon (TOC). Rocks below 6,000 ft have Type-III kerogens and low TOC values.

Coal-bearing rocks in the subsurface in the northern part of the Bellingham Basin, north of Bellingham, have historically been correlated with the Chuckanut and Huntingdon Formations (figs. 5). These rocks may be present throughout the Bellingham Basin subsurface and into Canada (fig. 61).

Discontinuous and lenticular deposits of subbituminous to low-volatile bituminous coal are in Tertiary nonmarine units overlying pre-Tertiary rocks similar to those in the Glacier area south of Bellingham (fig. 38). These rocks have been correlated to the Chuckanut Formation in the Bellingham area. The coal beds, which range from less than 1 ft to as much as 10 ft thick, crop out near the base of the Tertiary strata in the Coal Mountain area (figs. 38 and 40).

Upper middle Eocene and upper Eocene coal-bearing strata in the central and northern part of the Puget Lowland (figs. 38 and 62) (Beikman and others, 1961) belong to the undivided Puget Group (fig. 5) (Vine, 1969). Vine (1969) described coal distribution and reserves in the area, and compiled a 6,230-ft-thick stratigraphic section based on surface and shallow subsurface data. Fifty continuous and discontinuous beds of coal and carbonaceous shale are present in Vine's (1969) section. Borehole data indicate that coal-bearing strata extend down section for at least several hundred meters below Vine's (1969) section. In the Green River district (fig. 2), the Puget Group contains at least 16 major coal beds with a minimum cumulative thickness ranging from 73 to 90 ft; the coal-bearing strata is more than 6,300 ft thick. Coal rank ranges from subbituminous B to high-volatile A bituminous with most coals being high-volatile bituminous.

The Renton Formation (fig. 5) contains at least 10 coal beds with an aggregate mined thickness of at least 36 ft in a 2,180-ft-thick coal-bearing interval. Impure or bone coal and carbonaceous shale partings add another 80 ft to the coal-bearing interval.

The middle Eocene Carbonado and the upper Eocene Spiketon Formations of the Puget Group (fig. 5) contain coal and carbonaceous shale in the Wilkeson and Carbonado coal fields (fig. 2). The Carbonado Formation contains at least nine coal beds ranging in thickness from 2 to 8 ft. The coals are high-volatile A bituminous to low-volatile bituminous and are the most important coking coal deposits in Washington (Beikman and others, 1961).

The middle Eocene Skookumchuck Formation contains at least 13 coal beds with an aggregate thickness of about 88 ft in a coal-bearing interval that is about 2,600 ft thick. Coals range from lignite to subbituminous B (Beikman and others, 1961). Mean vitrinite reflectance of surface coals in the Skookumchuck range from 0.35 to 0.40, and subsurface values range from 0.40 to 0.70.

There are differences in the sedimentology of correlative coal-bearing strata in western Washington. For example Skookumchuck Formation in the Centralia mine has a greater proportion of brackish and shallow-marine rocks; whereas, the undivided Puget Group in the Black Diamond area contains a greater proportion of fluvial and (or) distributary channel and overbank deposits (Brownfield and others, 1994). This contrast reflects the more outboard (southwest) location of the Centralia area (fig. 41). In addition, positive relief caused during the deposition of the Eocene Northcraft Formation (volcanic center), which lies due east of Centralia (fig. 44), may have deflected fluvial channels to more southern and northern routes and isolated the Centralia area from fluvial influence. Although depositional environments as interpreted from the Centralia area show some fluctuation, nonmarine rocks become more dominant upward within each Eocene section and the overall regional trend is progradational.

The middle to upper Eocene Cowlitz Formation (fig. 5) of southwestern Washington contains coal and carbonaceous shale in the upper part of the formation (Roberts, 1958); it contains an aggregate thickness of about 70 ft of coal in at least seven beds in a 500-ft-thick section in the southern part of the area. Coals range from lignite to subbituminous B, but generally the coals are subbituminous C and have mean vitrinite reflectance values of about 0.40.

Gas has been collected and analyzed from 12 wells in the Jackson Prairie Gas Storage area (fig. 63) from three Skookumchuck and one Lincoln Creek sandstone reservoirs and is biogenic (Wurden and Ford, 1976). Torrent Energy (2008) reported preliminary testing of coal gas content to range from about 15–86 standard cubic feet (scf) per ton, averaging more than 50 scf per ton. Based on coal thickness, extent, rank, and gas content, the coalbed methane potential was estimated to more than 400 billion cubic feet of gas (Torrent Energy, 2008)

The middle Eocene Coaledo Formation in the Coos Bay Basin of Oregon contains numerous coals and carbonaceous shale beds. At least seven major coal beds are known in the lower member of the Coaledo Formation that contain numerous shale and bone coal partings. At least seven more coal beds are also in the upper member, with the informal Beaver Hill bed (5 to 6 ft thick) containing the greatest potential resources (Baldwin and others, 1973; Mason and Hughes, 1975). Many of the upper member coal beds contain shale and bone coal partings. Some of the historical producing mines were reported to contain gassy coals. The coals are subbituminous in rank and have heating values ranging from 9,260 to 10,080 Btu per pound on an as-received basis (Allen and Baldwin, 1944); they are characterized by an average moisture content of 17 percent, average ash content of 8 percent, and less than 1 percent sulfur (Baldwin and others, 1973).

The Spencer Formation contains thin coal beds associated with sandstone and carbonaceous shale. Thin coals and carbonaceous shale are common in the lower and upper parts of the formation just southeast of Portland, Oreg. (Al-Azzaby, 1980; Van Atta and Thoms, 1993). Several thin subbituminous coal beds have been reported in the southern part of the Oregon Coast Range (Wells and others, 2000). Spencer Formation coals are subbituminous to lignite along the eastern part of the central and northern Oregon Coast Range.

Assessment Units of Western Oregon and Washington Province

Three assessment units were defined within the Western Oregon and Washington Province in three total petroleum systems: (1) the Western Oregon and Washington Conventional Gas AU in the Cretaceous-Tertiary TPS, (2) the Tertiary Marine Gas AU in the Tertiary Marine TPS, and (3) the Eocene Coalbed Gas AU in the Tertiary Coalbed Gas TPS. Undiscovered gas resources were quantitatively estimated in each AU, and undiscovered oil resources were also quantitatively estimated in the Tertiary Marine Gas AU.

Hydrocarbon accumulations in the Western Oregon and Washington Conventional Gas AU and Tertiary Marine Gas AU are of the conventional type and were defined using the criteria established by Schmoker and Klett (1999). The gas accumulation in the Eocene Coalbed Gas AU is of the continuous type (unconventional) and was defined using criteria established by Schmoker (1999).

Based on a play concept (rather than an assessment unit concept), Johnson and Tennyson (1995) assessed the undiscovered hydrocarbons in seven conventional plays and three continuous (coalbed gas) plays within the Western Oregon and Washington Province. For the seven conventional petroleum plays (Johnson and Tennyson, 1995), a mean undiscovered hydrocarbon resource of 115.9 BCF (billion cubic feet) of gas and 19.3 MMB (millions of barrels) of oil was estimated. Mean estimated undiscovered gas resources from the three hypothetical coalbed-gas plays was 697.3 BCF (Johnson and Rice, 1995).

Western Oregon and Washington Conventional Gas Assessment Unit (50040101)

The Western Oregon and Washington Conventional Gas AU within the Cretaceous-Tertiary Composite TPS (fig. 70) is defined to include the area in which potential reservoir and source rocks are known to exist or inferred to exist and where hydrocarbon source rock thermal maturities have reached a vitrinite reflectance (R_O) of 0.5 percent or greater. Gas generated from potential source rocks is interpreted to have migrated into lower to upper Eocene reservoir rocks. This AU is classified as frontier on the basis of the existence of at least one producing field in the AU (the Mist gas field).

The Western Oregon and Washington Conventional Gas AU likely underlies much of the central part of the Western Oregon and Washington Province (fig. 70) and extends southward from the Canadian border to the Klamath Mountains of Oregon; it contains about 11.1 million acres. The gas accumulations in this AU are of the conventional type and were defined using the criteria established by Schmoker and Klett (1999).

An events chart (fig. 71) for the Western Oregon and Washington Conventional Gas AU graphically portrays the ages of source, seal, and reservoir rocks, and timing of trap development, generation, accumulation, migration, and preservation of hydrocarbons.

The Bellingham Basin (fig. 61) is the northernmost basin in the AU and extends into Canada. Only the United States part of the basin is assessed as part of this AU. The northwestern boundary extends into the Strait of Georgia and the Strait of Juan de Fuca to the Canadian border. The northeastern boundary is the uplifted pre-Tertiary basement rock complex, the eastern boundary is the western foothills of the Cascade Range, and the southern boundary is the Klamath Mountains of Oregon and extends offshore to the 3-mile limit of State waters in southwestern Oregon. From southwestern Oregon north to Puget Sound, the western AU boundary generally follows the eastern part of the Oregon and Washington Coast Ranges.

Northwest of Bellingham, Wash. (fig. 61), thermogenic gas has been sampled from old well casings and contains high levels of methane and nitrogen (McFarland, 1983; Hurst, 1991). One abandoned well vented about 10,000 ft^3 of gas per day (McFarland, 1983). Between 1988 and 1991 three wells were drilled in Bellingham Basin with depths ranging from 4,422 to 9,126 ft and gas shows were reported from several sandstone and coal beds (Johnson and others, 1997).

Modeling of burial history, thermal maturity, and timing of hydrocarbons in the central part of the Western Oregon and Washington Conventional Gas AU by Armentrout and

Figure 70. Western Oregon and Washington Conventional Gas Assessment Unit located in western Oregon and Washington; boundary shown in blue. Boundary of Western Oregon and Washington Province shown in red; boundary of Cretaceous-Tertiary Total Petroleum System shown in orange. Locations of the Coos Bay coal field shown as a solid brown oval and the Mist gas field shown as a solid red circle.

Suek (1985) indicated that maturation of Cowlitz Formation source rocks may have begun in the middle Oligocene (fig. 72). Modeling of burial history for the pre-Tertiary rocks, the Bushnell Rock Formation, and the lower part of the Tenmile Formation of the lower Eocene Umpqua Group in the southern Oregon Coast Range indicates that maturation of source rocks occurred as early as middle Eocene (fig. 73) (Ryu and others, 1996). In the central part of the Oregon Coast Range, modeling of the burial history of strata penetrated in the General Petroleum Long Bell No. 1 well (total depth, 9,004 ft) indicates that Umpqua Group source rocks entered the hydrocarbon maturation window in the middle Eocene and that thermogenic gas generation began in the Oligocene when depth of burial exceeded 14,000 ft (fig. 74) (Ryu and others, 1996).

In the northern part of the AU, the reservoirs are the lower to middle Eocene Chuckanut Formation and possibly the upper Eocene to Oligocene Huntingdon Formation fluvial and distributary channel arkosic sandstones that are as much as 200 ft thick (Johnson, 1982, 1984a,b). Porosity and permeability are marginal and probably decrease with depth because of the alteration of feldspar and lithic rock fragments (Johnson and others, 1997). Fluvial deposition that produced the thick Chuckanut Formation must have also produced thick deltaic and continental shelf facies, as yet not identified possibly because of being transported northward by strike-slip faulting to form an exotic terrane in the Gulf of Alaska. Johnson (1984c) postulated that transcurrent faulting that truncated the Chuckanut Formation corresponds to west- and northwest-trending faults on Vancouver Island. Traps are likely large

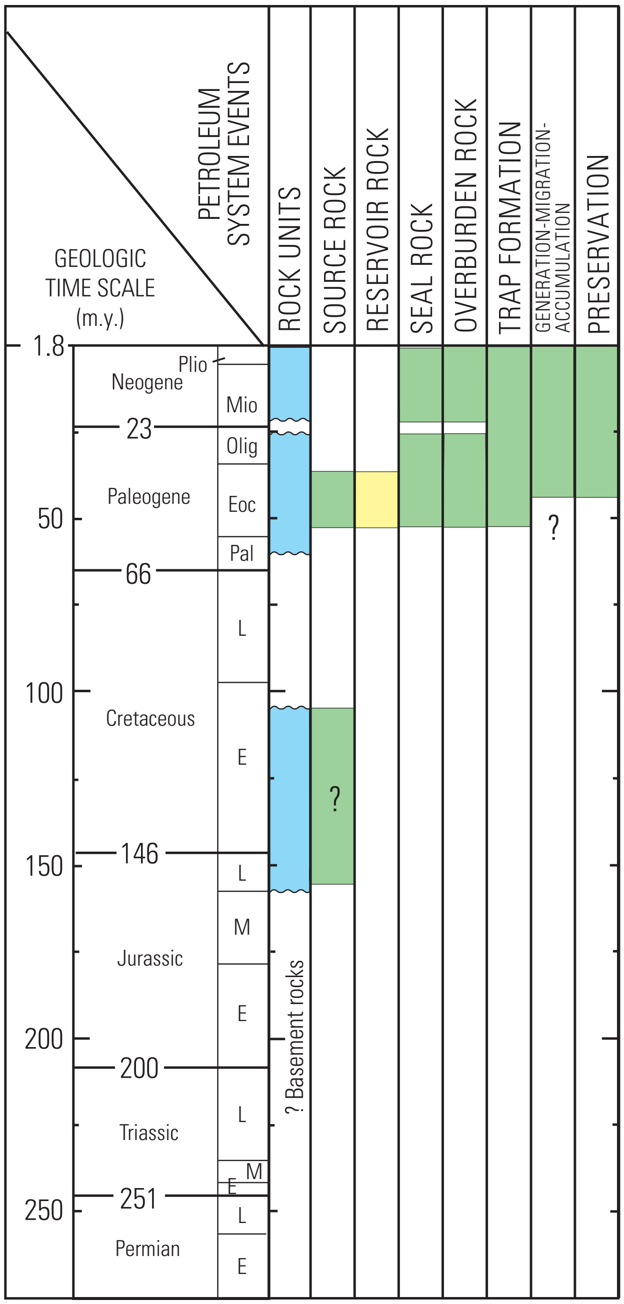

Figure 71. Events chart for the Western Oregon and Washington Conventional Gas Assessment Unit in the Western Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the time of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Geologic time scale in millions of years (m.y.). Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; M, Middle; E, Early.

anticlines—for example Hurst (1991) calculated 5,000 acres of closure on an anticline penetrated by the AHEL Birch Bay No. 1 well (fig. 61)—and structural traps related to high-angle faults in the Bellingham Basin area (Johnson, 1982; Mustard and Rouse, 1994). Seals are fine-grained fluvial rocks but are generally lenticular, which could permit potential leakage from the reservoirs. Maximum burial and hydrocarbon generation was during the late middle to early late Eocene before the late Eocene folding and uplift (Johnson and others, 1997).

Within the central and southeastern parts of the Puget Lowland (fig. 62), reservoirs are (1) marine lithic-rich sandstones of the lower and middle Eocene Raging River Formation of the Puget Group and deeply buried equivalent units in the Seattle Basin; and (2) fluvial- and distributary-channel sandstones in the middle to upper Eocene Carbonado, Raging River, Renton, Spiketon, and Tiger Mountain Formations and the undifferentiated Puget Group. The fluvial sandstone units are generally arkosic with thicknesses ranging from 10 to more than 200 feet. Petrographic data indicate that the sandstones are "tight" in the eastern part of the Puget Lowland (Johnson and others, 1997) due to alteration of feldspar and lithic rock fragments. Sandstone units analyzed from two cores near Black Diamond, Wash. (fig. 62), revealed porosities from 6 to 37 percent and permeability ranging from 1 millidarcy to 2 darcies. Traps are most likely anticlines and fault blocks, like the large Kingston arch within the northern Seattle Basin (Johnson and others, 1994), and smaller complex structures such as those in the Black Diamond and Morton areas of the of the western Cascade Range (fig. 62). Similar structures may be present in the Everett and Tacoma Basins. Seals are fine-grained marine and nonmarine Eocene rocks and possibly Oligocene volcanic rocks. Maximum burial and the onset of hydrocarbon generation occurred in the late Eocene and Oligocene before Oligocene to Neogene folding and uplift (Johnson and others, 1997). Regional heat flow was elevated during the formation of the Cascade Range in the early Oligocene and Miocene, possibly accelerating hydrocarbon generation. Because of the ongoing tectonism in the Pacific Northwest, structural traps within the AUs have most likely formed before, during, and after hydrocarbon generation.

The southernmost part of the Puget Lowland and the Chehalis Basin (fig. 63) contain potential reservoir rocks in the middle to upper Eocene Cowlitz, Skookumchuck, and McIntosh Formations (fig. 5). The Cowlitz and Skookumchuck Formations contain fluvial, deltaic, and shallow-marine arkosic sandstones as much as 170 ft thick; sandstone reservoirs within the Jackson Prairie gas storage well (fig. 63) have porosities of 30 to 40 percent and permeabilities as high as 8.5 darcies (Wurden and Ford, 1976). The Skookumchuck sandstones are comparable to those reported from the Mist gas field of northwestern Oregon (figs. 2 and 63), where hydrocarbons are produced from Cowlitz Formation sandstones. Turbidite sandstone reservoirs in the McIntosh Formation are as thick as 100 ft and have porosities of 10 to 20 percent and permeabilities less than 6.2 mD (Moothart, 1992). Porosity in these McIntosh reservoir rocks is degraded by the presence of clays,

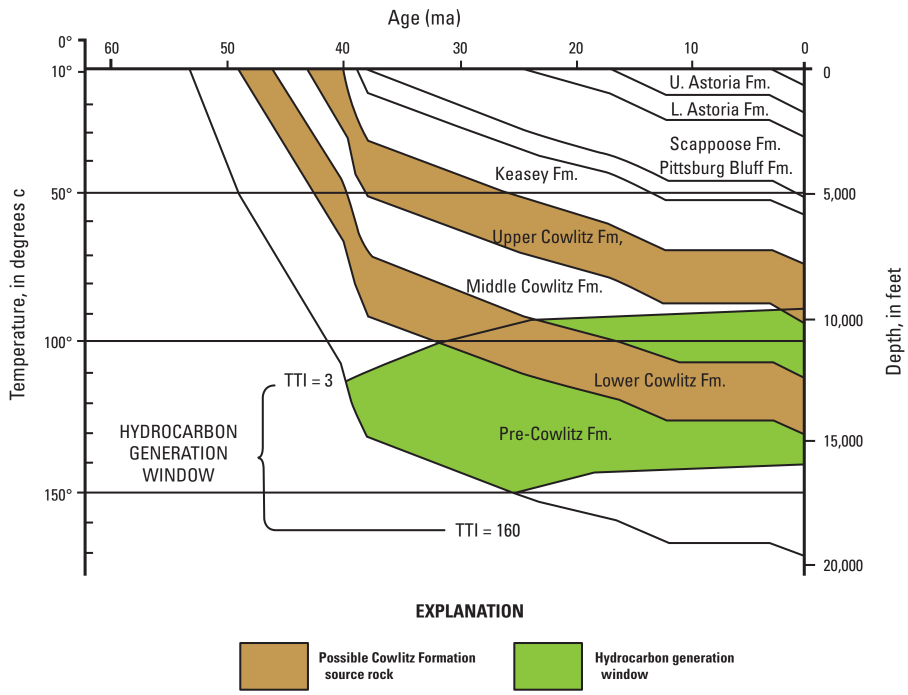

Figure 72. Burial history model for strata in the northern part of the Willamette Valley, using the Lopatin model (Waples, 1980). Green window represents the calculated hydrocarbon generation window. Possible source rocks in upper and lower parts of Cowlitz Formation shown in brown. Overlapping area represents potential source rocks within generation window. Rocks of the lower part of Cowlitz Formation entered the generation window at 33 million years before present (Ma) and rocks of the upper Cowlitz Formation entered the generation window at 3 Ma. Formation thicknesses are from Ryu and others (1992). TTI, time-temperature index. Thermal history (calculated using a steady state heat flow of 1.5°F per 100 ft). Modified after Armentrout and Suek (1985).

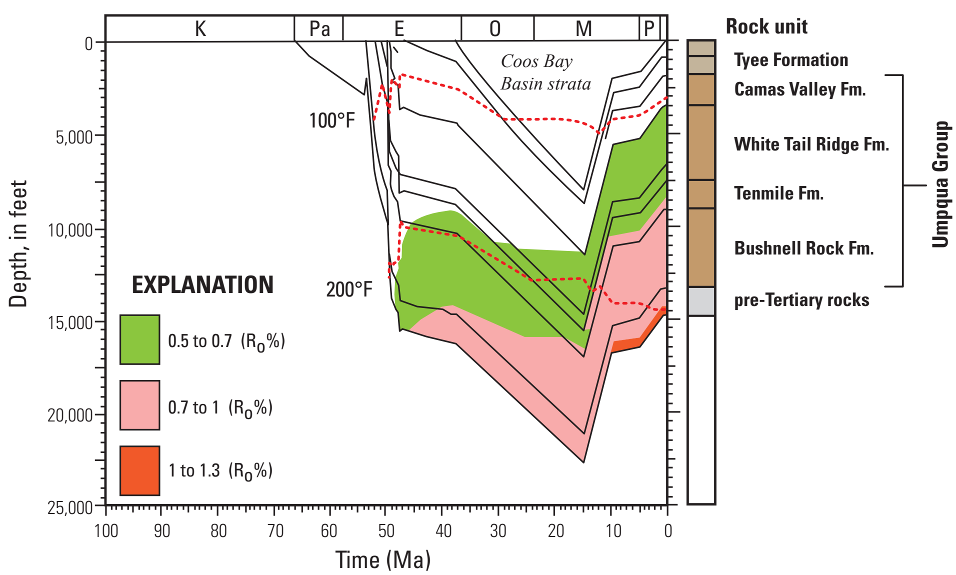

Figure 73. Burial history model for strata in the southern part of the Tyee Basin using the Twentymile measured section modified after Ryu and others (1992). Red dashed line represents time-temperature index curve. Formation thicknesses are from Ryu and others (1992). Thermal history is calculated using a steady state heat flow of 1.27°F per 100 ft. Maturity was derived from Lawrence Livermore National Laboratories Easy Percent R_0. Time interval for calculation of maturity and expulsion is five. Expulsion is based on vitrinite reflectance (R_0). K, Cretaceous; Pa, Paleocene; E, Eocene; O, Oligocene; M, Miocene; P, Pliocene. Ma, millions of years before present.

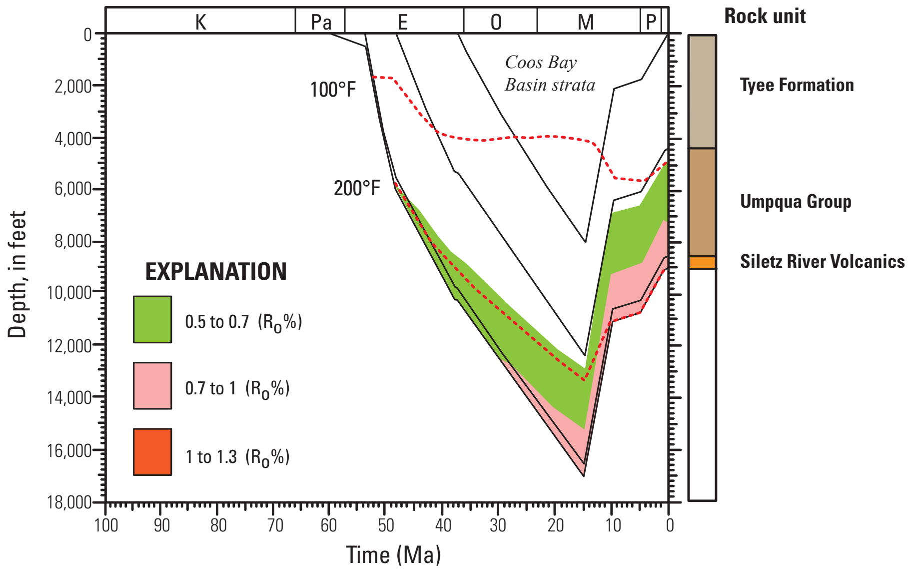

Figure 74. Burial history model for strata in the General Petroleum Long Bell No. 1 well (total depth, 9,004 ft) located in the central part of the Tyee Basin (see fig. 13); modified after Ryu and others (1992). Red dashed line represents time-temperature index curve. Formation thicknesses are from Ryu and others (1992). Thermal history is calculated using a steady state heat flow of 1.27°F per 100 ft). Maturity was derived from Lawrence Livermore National Laboratories Easy Percent R_0. Time interval for calculation of maturity and expulsion is five. Expulsion is based on vitrinite reflectance (R_0). K, Cretaceous; Pa, Paleocene; E, Eocene; O, Oligocene; M, Miocene; P, Pliocene. Ma, millions of years before present.

zeolites, and calcite. Traps are most likely fault blocks similar to the Mist field (fig. 75), that is, small folds with shallow dipping limbs, and stratigraphic traps formed by nearshore or deltaic sandstone units enclosed by mudstone (Armentrout and Suek, 1985; Niem and others, 1994). As with the central and southeastern parts of the Puget Lowland, ongoing tectonism in the Pacific Northwest likely formed structural traps within this area of the Western Oregon and Washington Conventional Gas AU before, during, and after hydrocarbon generation. Seals are overlying fine-grained mudstones and siltstones of the Lincoln Creek Formation (fig. 5) and interbedded marine mudstones and siltstones associated with the McIntosh turbidites. Maximum burial and the onset of hydrocarbon generation occurred in the Miocene (Johnson and Tennyson, 1995). Regional heat flow was possibly elevated during the middle Miocene by local heating from the Miocene Columbia River Basalt Group (Esposito and Whitney, 1995).

The Cowlitz Formation reservoir in the Mist gas field (figs. 2 and 63) is the informal Clark and Wilson sandstone sequence (fig. 75) of the Cowlitz Formation (Armentrout and Suek, 1985), which has reported porosities ranging from 25 to 36 percent and permeabilities of 20 millidarcies to about 7 darcies (Alger, 1985; Armentrout and Seek, 1985; Niem and others, 1994). The Clark and Wilson sandstone sequence is about 600 ft thick in the field area and consists of fine- to medium-grained arkosic shallow-marine sandstone and interbedded mudstone. Traps are complex and at least 13 compartmented gas pools are known (Armentrout and Suek, 1985). Traps consist of faulted anticlines, and seals are transgressive shales in the upper parts of the Cowlitz and Keasey Formations (fig. 75). The Keasey Formation shales are tuffaceous, and the volcaniclastic material has been altered to montmorillonite, an expandable clay. Stratigraphic traps are present in the Cowlitz Formation and consist of thin sandstone encased in shale (Armentrout and Suek, 1985). The Clark and Wilson sandstone sequence is equivalent to a thick sandstone unit in the Spencer Formation south of the Mist gas field where Schlicker (1962) reported sandstone porosities ranging from 32 to 41 percent and permeabilities from 184 mD to about 4.5 darcies. Thermal modeling indicates that maturation and onset of hydrocarbon generation of the Cowlitz Formation source rocks probably occurred in the Oligocene (fig. 72) (Armentrout and Suek, 1985). Regional heat flow was possibly elevated during the middle Miocene by local heating from the Miocene Columbia River Basalt Group.

Probable reservoir rocks in the central and southern part of the Western Oregon and Washington Conventional Gas AU are (1) fan-delta and shelf- or slope-channel sandstone of the Bushnell Rock Formation and fluvial and deltaic sandstones of White Tail Ridge Formation of the lower Eocene Umpqua Group (fig. 13) (Niem and others, 1992; Wells and others, 2000), (2) shelf and slope arkosic sandstones of the upper and middle Eocene Tyee Formation, and (3) nonmarine and marine sandstones in the middle Eocene Coaledo Formation (fig. 8). Reservoir facies vary greatly in thickness and quality. The White Tail Ridge Formation sandstones have the highest reservoir potential (Ryu and others, 1996) and consist of delta-front sandstone units with porosities up to 17.0 percent and permeabilities as much as 154 millidarcies (Niem and Niem, 1990; Ryu and others, 1996) and thicknesses ranging from a few feet to 30 ft. Traps are most likely early Tertiary folds and faults with possible stratigraphic traps associated with the shelf- and-slope channel sandstones. Seals are marine and nonmarine interbedded mudstones and siltstones. Some Tyee Basin sandstones in the Umpqua Group and Tyee Mountain Member of the Tyee Formation could be potential tight gas reservoirs because they have low porosity and permeability (Law and Spencer, 1993; Ryu and others, 1996). The General

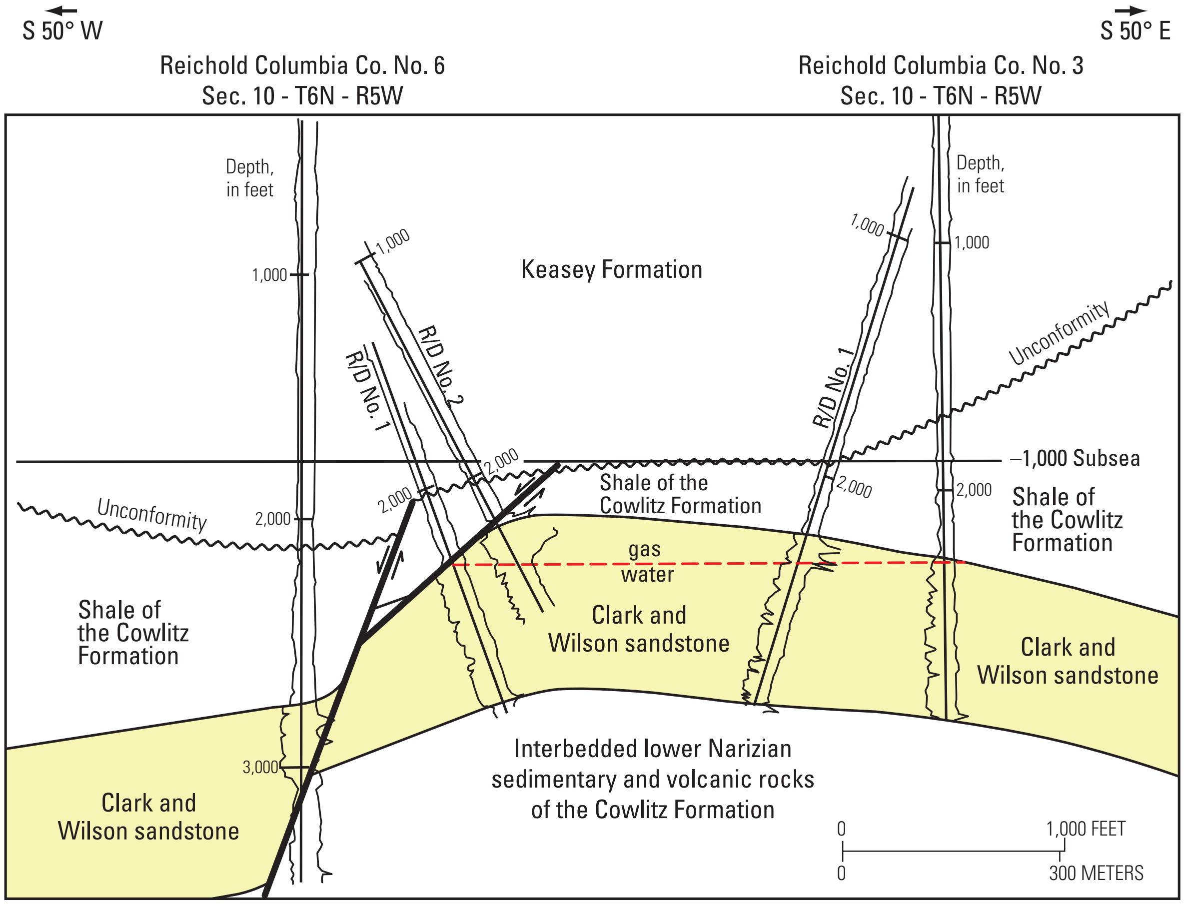

Figure 75. Northeast–southwest cross section through Reichold Energy Corporation Columbia County Nos. 6 and 3 wells in the Mist gas field, west of Portland, Oregon, showing the trapping of hydrocarbons in the informal Clark and Wilson sandstone that resulted from faulting against the shales of the Cowlitz Formation, as well as from the unconformable relations with the overlying Keasey Formation. Modified after Bruer (1980) and Armentrout and Suek (1985). R/D, Redrill of Reichold Columbia Co. No. 3 (No. 1) and Reichold Columbia Co. No. 6 (Nos. 1 and 2) development wells.

Petroleum Long Bell No. 1 well appears to be overpressured at a depth of 6,970 ft (Ryu and others, 1996). These potential tight-gas sandstone accumulations were not assessed.

Modeling of burial history, thermal maturity, and timing of hydrocarbon generation within the Tyee forarc basin (figs. 73 and 74) indicates that the lower part of the Umpqua Group could have entered the oil generation window during the middle Eocene, and the Tenmile Formation entered the oil generation window in the late Eocene, and both have now reached moderate levels of maturity (>0.7 R_0 percent). Today, the White Tail Ridge and Camas Valley Formations are within the oil window at depths ranging from 8,500 to 14,500 ft.

Gas seeps (mainly biogenic) and two oil seeps (Niem and Niem, 1990) indicate the presence of mature source rocks within the province; the oil seeps may be derived from sources in Mesozoic mudstones in Klamath melange terranes including the Myrtle Group and Dothan Formation. Biogenic gas seeps in deltaic facies of the White Tail Ridge Formation of the Umpqua Group west of Roseburg, Oreg. (fig. 9), appear to be related to interbedded coal and carbonaceous mudstones (Ryu and others, 1996).

The Western Oregon and Washington Conventional Gas AU currently has only one producing gas field, the Mist field. The AU is given a geologic probability of 1.0 because there is sufficient evidence that there are adequate reservoirs, traps, and seals (appendix A). The estimated minimum, mode, and maximum numbers of undiscovered gas accumulations are 1, 8, and 70, respectively, and the estimated minimum, median, and maximum sizes of undiscovered gas accumulations are 3, 10, and 300 BCFG, respectively.

The assessed mean undiscovered volumes in the Western Oregon and Washington Conventional Gas AU are 454 BCF of estimated conventional gas (table 2) and 1.0 million barrels of natural gas liquids (MMBNGL). The estimated mean size

Table 2. Western Oregon and Washington Province assessment results.

[MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas accumulations, all liquids are included as the NGL (natural gas liquids). Undiscovered gas resources are the sum of non-associated and associated gas. F95 represents a 95 percent chance of at least the amount tabulated; other fractiles are defined similarly. TPS, total petroleum system; AU, assessment unit; CBG, coalbed gas. Gray shading indicates not applicable]

	Total Petroleum System (TPS) and Assessment Unit (AU)	Field Type	Total Undiscovered Resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Conventional Resources	**Cretaceous-Tertiary Composite TPS**													
	Western Oregon and Washington Conventional Gas AU	Oil	0	0	0	0	0	0	0	0	0	0	0	0
		Gas					79	403	1,000	454	0	1	2	1
	Tertiary Marine TPS													
	Tertiary Marine Gas AU	Oil	2	9	45	15	3	14	70	22	0	1	4	1
		Gas					34	195	646	249	1	5	17	6
	Total Conventional Resources		**2**	**9**	**45**	**15**	**116**	**612**	**1,716**	**725**	**1**	**7**	**23**	**8**
Continuous Resources	**Tertiary Coalbed Gas TPS**													
	Eocene Coalbed Gas AU	CBG	0	0	0	0	565	1,307	3,024	1,489	0	0	0	0
	Total Continuous Resources		**0**	**0**	**0**	**0**	**565**	**1,307**	**3,024**	**1,489**	**0**	**0**	**0**	**0**
	Total Undiscovered Oil and Gas Resources		**2**	**9**	**45**	**15**	**681**	**1,919**	**4,740**	**2,214**	**1**	**7**	**23**	**8**

of the largest expected gas field is 85 BCFG, and the estimated gas volume (454 BCF) is about 20 percent of the total estimated mean of 2,214 BCF of gas in the Western Oregon and Washington Province.

Tertiary Marine Gas Assessment Unit (50040201)

The Tertiary Marine Gas AU within the Tertiary-Marine TPS lies in the westernmost part of the Western Oregon and Washington Province (fig. 76). Currently, there is no petroleum production within the AU, so it is categorized as being 'hypothetical." However, as discussed below, there is sufficient evidence in the form of numerous gas and oil seeps as well as the past production of some 12,000 barrels of oil near Ocean City, Wash., to indicate the presence of mature source rocks, adequate reservoir and source rocks, and potential traps.

The hypothetical Tertiary Marine Gas AU includes thick successions of Paleogene marine sandstone and shale and fluvial to deltaic arkosic sandstone and interbedded mudstone, carbonaceous shale, and coal. The AU boundary is defined to include the areas in which potential Tertiary marine- and marginal-marine reservoirs and gas-prone source rocks are known to exist or inferred to exist and where hydrocarbon source rock thermal maturities have reached a vitrinite reflectance (R_O) of 0.5 percent or greater. The hydrocarbon accumulations in this AU are of the conventional type and were defined using the criteria established by Schmoker and Klett (1999). Normal pressured gas generated from potential source rocks is interpreted to have migrated into Eocene to Miocene reservoir rocks. The TPS boundary includes the Tofino-Fuca Basin Gas, Western Washington Melange, Southwest Washington Miocene Sandstone, and the Astoria plays of Johnson and Tennyson (1995) and Johnson and others (1997).

The AU extends southward from the Canadian border in the Strait of Juan de Fuca, likely underlies the Olympic Peninsula in the northwestern part of Washington, and extends southward along the Washington coastal area to the northwestern part of the Oregon coastal area in the Western Oregon and Washington Province (fig. 76); it contains about 3.6 million acres.

An events chart (fig. 77) for the Tertiary Marine Gas AU graphically portrays the ages of source, seal, and reservoir rocks, and the timing of trap development, generation, accumulation, migration, and preservation of hydrocarbons.

In the northern part of the AU, more than 28,000 ft of north-dipping Eocene to lower Miocene strata contain gas-prone source rocks (fig. 65) (Niem and Snavely, 1991). These rocks are most likely deeply buried Eocene marine mudstones

Figure 76. Tertiary Marine Gas Assessment Unit in western Oregon and Washington; boundary shown in green. Boundary of Western Oregon and Washington Province shown in red. Location of the Coos Bay coal field shown as a solid brown oval and the Mist gas field shown as a solid red circle.

located in the offshore part of the Tofino-Juan de Fuca Basin (figs. 48 and 65) and contain Type-III kerogen and 0.3- to 1.2-percent total organic carbon (Snavely and others, 1980; Niem and Snavely, 1991). Potential reservoir rocks are upper Eocene to Oligocene turbidite sandstones of the Twin River Group (figs. 5 and 47) (Snavely and others, 1980; Niem and Snavely, 1991), in which the best reservoirs have porosities ranging from 20.4 to 24.6 percent and permeabilities ranging from 2 to 657 mD (Niem and Snavely, 1991). Turbidite sandstone beds can be as thick as 40 ft, with composite sandstone units having thicknesses as much as 400 ft. Possible stratigraphic traps include buried turbidite channels and sandstone beds; small fault-related structural traps may also be present. Seals consist of marine mudstones interbedded with the turbidite sandstone bodies. Thermogenic gas seeps have been identified in the northern part of the AU, indicating that the source rocks have reached maturity and generated hydrocarbons (fig. 65) (Snavely and Kvenvolden, 1989). Lingley (1986) reported that one gas seep flowed at the rate of 20 thousand cubic feet of gas per day. Maturation and migration probably occurred in the Miocene, during maximum burial of the Juan de Fuca Basin strata, and the Ozette melange and other middle and upper Eocene units occur below the thrust fault (fig. 48). Migration was probably along faults and updip within the Twin River Group turbidite reservoirs.

Eocene to Oligocene Ozette terrane and Oligocene to middle Miocene Hoh rock assemblage (fig. 5) (Snavely and Kvenvolden, 1989) contain marine-turbidite channel

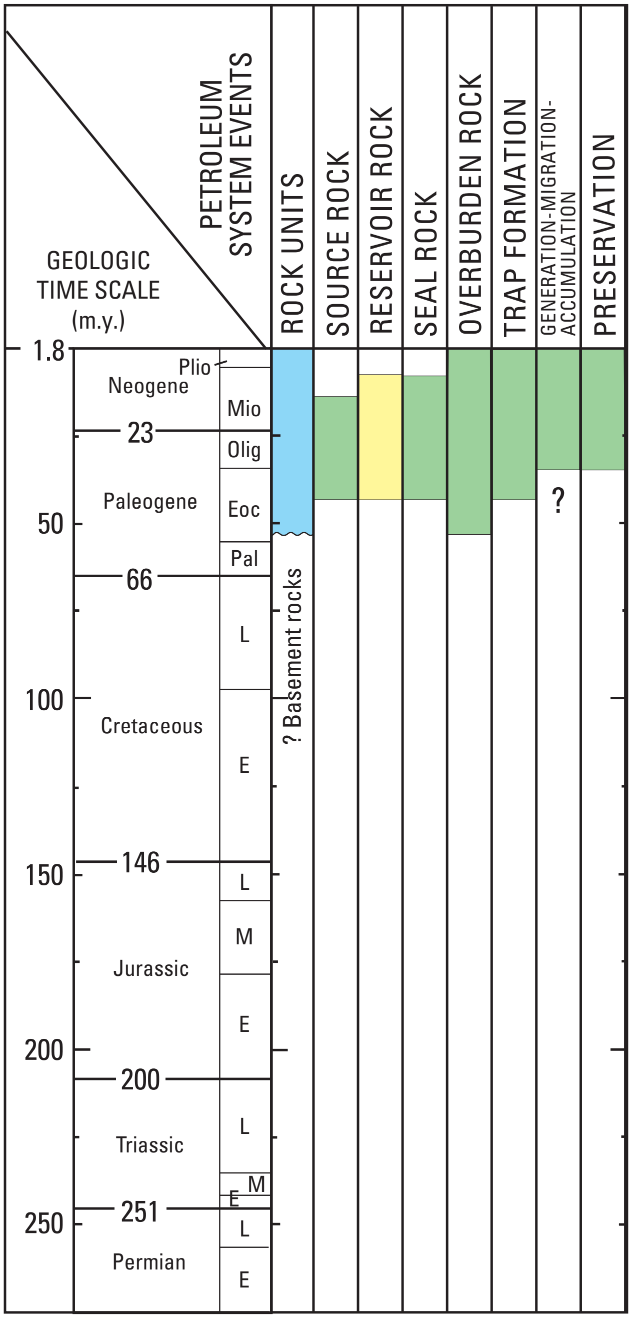

Figure 77. Events chart for the Tertiary Marine Gas Assessment Unit in the Tertiary-Marine Total Petroleum System in the Western Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the time of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Geologic time scale in millions of years (m.y.). Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; M, Middle; E, Early.

sandstones in coherent structural blocks that are possible reservoir rocks and are inferred to exist through much of the northwestern part of the Tertiary-Marine AU (figs. 50, 51, and 66). Palmer and Lingley (1989) reported that sandstone units in the Grays Harbor area (fig. 1) range from 10 to 100 ft in thickness, and composite sandstone units are as thick as 140 ft (Lingley, 1995). Porosities are generally less than 25 percent and permeabilities are less than 100 mD (Palmer and Lingley, 1989). Potential traps in the Ozette terrane and Hoh rock assemblage include fault blocks and anticlines, as well as stratigraphic and fault-related traps within the underthrusted turbidites in the Olympic accretionary wedge (figs. 50 and 56). Seal rocks are fine-grained rocks within the Ozette and Hoh sequences. Numerous oil and gas shows are reported in exploration wells, and several oil and gas seeps are along the northwestern Washington coast (figs. 65 and 66). Migration and generation of hydrocarbons within this part of the Tertiary Marine Gas AU most likely occurred from the Oligocene to the present, as the Ozette terrane and Hoh rock assemblage were continually being underthrusted beneath the continental margin. Migration of the hydrocarbons from the mature source rocks is upward and westward along faults (Snavely and Kvenvolden, 1989; Palmer and Lingley, 1989). The lower and middle Miocene Angora Peak, Youngs Bay, and Wickiup Mountain members of the Astoria Formation (fig. 5), informally named by Niem and Niem (1985), contain potential reservoir rocks. The deltaic Angora Peak member is as much as 1,000 ft thick and contains crossbedded, fine-grained arkosic sandstone and conglomerate. The Youngs Bay member is about 1,100 ft thick and contains thick beds of medium- to fine-grained sandstone beds. The Wickiup Mountain member is about 1,300 ft thick and contains friable fine-grained sandstone beds. The potential Astoria Formation reservoir rocks have porosities ranging from 26 to 35 percent and permeabilities of 92 to 270 mD (Niem and Niem, 1985). Potential reservoirs also include marginal marine and deltaic sandstone of the Montesano Formation (fig. 5). Palmer and Lingley (1989) reported that a 600-ft-thick sandstone in the Montesano in the Grays Harbor area (fig. 67) averaged 28 percent porosity and 1 darcy permeability. Several sandstone beds as much as 100 ft thick were encountered in drill holes penetrating the Astoria and Montesano Formations east of Aberdeen (fig. 54), indicating that potential reservoirs may exist at depth. Traps are most likely fault traps adjacent to normal or oblique-slip faults of post-Miocene age (Johnson and Tennyson, 1995). Other potential traps within the Miocene units include small anticlines associated with thrusting and possible stratigraphic pinchouts of submarine channels within the Astoria and Montesano Formations. Seals are fine-grained rocks within these formations. Migration and generation of hydrocarbons most likely began in the latest Miocene after potential Miocene reservoirs were deposited. Regional heat flow was possibly elevated during the middle Miocene by local heating from the Miocene Columbia River Group.

The presence of an unknown, oil-prone source rock in the TPS is evidenced by numerous oil seeps and approximately 12,000 barrels of oil produced from the Hoh rock assemblage in one well near Ocean City, Wash., from 1957 to 1961 (fig. 66) (McFarland, 1983; Palmer and Lingley, 1989).

The AU is given a geologic probability of 1.0 because there is sufficient evidence that the AU has adequate reservoirs, traps, and seals (appendix B). The estimated minimum, mode, and maximum numbers of undiscovered gas accumulations are 1, 5, and 30, respectively, and the estimated minimum, median, and maximum sizes of undiscovered gas accumulations are 3, 8, and 800 BCFG, respectively. The estimated minimum, mode, and maximum numbers of undiscovered oil accumulations are 1, 2, and 10, respectively; the estimated minimum, median, and maximum sizes of undiscovered oil accumulations are 0.5, 1.3, and 130 MMBO.

The USGS assessed mean undiscovered volumes in the Tertiary Marine Gas AU are 249 BCF of estimated conventional gas (table 2) and 6 MMBNGL. The estimated mean size of the largest expected gas field is 101 BCFG, and the estimated gas volume (249 BCF) is about 11 percent of the total estimated mean of 2,214 BCF of gas in the Western Oregon and Washington Province. The assessed mean undiscovered volume of oil is 15 MMBO with an estimated mean of 22 BCF associated gas and 1 MMBNGL. The mean size of the largest expected oil field is 9 MMBO.

Figure 78. Eocene Coalbed Gas Assessment Unit in western Oregon and Washington; boundary shown in blue. Boundary of Western Oregon and Washington Province is shown in red. Locations of the Coos Bay coal field shown as a solid brown oval and the Mist gas field shown as a solid red circle.

Eocene Coalbed Gas Assessment Unit (50040381)

The Eocene Coalbed Gas AU within the Tertiary Coalbed Gas TPS of the Western Oregon and Washington Province (fig. 78) is also classified as hypothetical because there are no currently producing fields. The coincident TPS and boundary is defined on the basis of where Paleogene coal-bearing units are known to exist or inferred to exist and where the coals and carbonaceous shales are less than 6,000 ft below the surface. The coals serve as both source and reservoir rocks. Coals and carbonaceous shales greater than 6,000 ft were not assessed due to the potential decrease in permeability that could affect coalbed-gas recovery. Gas resource potential within the coals can be enhanced by the entrapment of migrated gas from other source rocks such as interbedded carbonaceous shale.

The hypothetical Eocene Coalbed Gas AU likely underlies much of the central part of the Western Oregon and Washington Province (fig. 78), extending southward from the Canadian border to the Klamath Mountains of Oregon; it contains about 11.1 million acres. The gas accumulations expected to be in this AU are of the continuous type (unconventional)

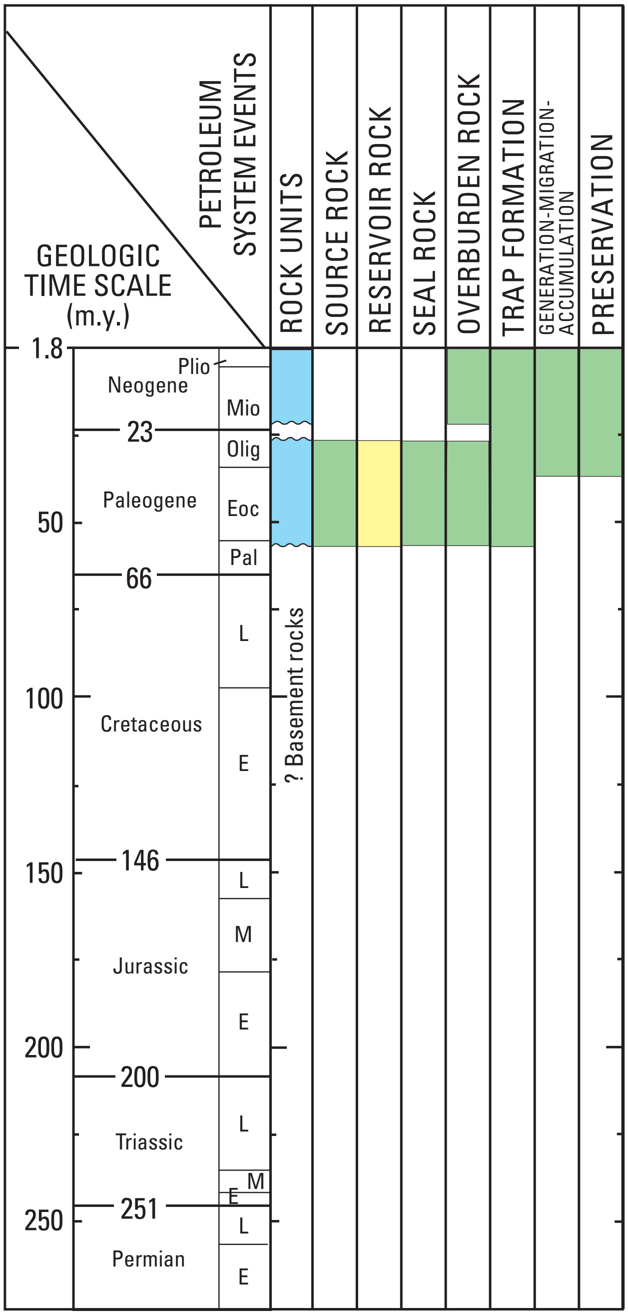

Figure 79. Events chart for the Eocene Coalbed Gas Assessment Unit in the Tertiary Marine Total Petroleum System in the Western Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the time of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Geologic time scale in millions of years (m.y.). Plio, Pliocene; Mio, Miocene; Olig, Oligocene; Eoc, Eocene; Pal, Paleocene, L, Late; M, Middle; E, Early.

and were defined using the criteria established by Schmoker (1999).

An events chart (fig. 79) for the Eocene Coalbed Gas AU graphically portrays the ages of source, seal, and reservoir rocks, as well as the timing of trap development, generation, accumulation, migration, and preservation of hydrocarbons.

Within the Bellingham Basin (fig. 61) the Chuckanut Formation contains at least 15 coal beds ranging in thickness from 2 to about 25 ft (Jenkins, 1923, 1924; Beikman and others, 1961). Two main coal zones are in Whatcom and Skagit Counties, Wash.—the Blue Canyon coal zone at the base of the Chuckanut Formation and the Bellingham coal zone also in the Chuckanut Formation. Jordan Exploration Company (2002) reported individual coal beds ranging from 1 to 16 ft thick with at least seven beds with thicknesses ranging from 6 to 16 ft and a potential aggregate coal thickness of more than 90 ft. In the Bellingham Basin-Whatcom County coal area (fig. 2), historical mining reports state that the coals were gassy. Over 95 old gas wells have been drilled in the Bellingham Basin (figs. 2 and 61) and most produced minor gas from Quaternary deposits-Chuckanut or Huntingdon Formation contact zone (Jordan Exploration Company, 2002). Only one desorbtion test has been reported for coals in the Bellingham Basin; it yielded 100 scf per ton (Johnson and others, 1997). Pappajohn (1991) reported four factors that are encouraging for the exploration of coalbed methane in the Bellingham area: (1) the presence of strata known to contain high-volatile bituminous coal at suitable depths with coalbed methane, (2) reports of methane in coal mining records, (3) the many gas shows from oil and gas wells penetrating the Eocene coal-bearing strata, and (4) gas produced from shallow water wells trapped below the glacial deposits in the Ferndale gas field northwest of Bellingham.

The coalbed-gas sources in the Puget Lowland (fig. 44) and foothills of the western Washington Cascade Mountains are coals within the Puget Group and its Renton, Carbonado, and Spiketon Formations (fig. 5). The net coal thickness in the Puget Group is 90 ft in about 6,300 ft of section, and the coal rank ranges from subbituminous B to high-volatile A bituminous with most being high-volatile B bituminous (Vine 1969). The Renton Formation contains at least 10 coal beds in the Tiger Mountain area (fig. 62) with a net thickness of at least 36 ft in a 2,180-ft-thick coal-bearing interval. The Carbonado Formation contains at least 16 coal beds, of which nine beds range from 2 to 8 ft thick, and the coals range in rank from high-volatile A bituminous to medium-volatile bituminous.

Fifteen exploration wells drilled since 1986 could be interpreted as coalbed-gas wells; a few wells were subjected to production testing (Pappajohn and Mitchell, 1991). Good gas shows were encountered in several wells, but there is presently no coalbed-gas production. Pappajohn and Mitchell (1991) reported desorbtion values ranging from 218 to 564 scf per ton and averaging 423 scf per ton for five coalbeds penetrated by drilling in the Wilkeson area (fig. 62). Analyzed gas samples contained slightly less than 99 percent methane and minor amounts of nitrogen and carbon dioxide. Historical mining records accounts of underground mine accidents in the region related to methane and the presence of biogenic gas ($\delta^{13}C$ = –71.11) bubbling to the surface through ponds in the John Henry No. 1 mine near Black Diamond, Wash. (fig. 62), reported by Brownfield and others (1994, 2005) are further indicators of gassy coals (Brownfield and others, 1994). Pappajohn and Mitchell (1991) reported analytical data that indicated that water produced from coal seams in the Wilkeson area meets State and Federal requirements for surface discharge.

In the Chehalis Basin area near Centralia, Wash. (fig. 63), the Skookumchuck Formation (fig. 5) contains gas-bearing coals as much as 40 ft thick. Duncan Oil Company, Inc. (2002) reported that desorbtion tests on coals recovered from the Duncan NWCH 42–9A well measured as high as 86 scf per ton in the 40-ft-thick Blue coal bed. Biogenic gas was collected and analyzed from 12 wells in the Jackson Prairie gas storage area from three sandstone reservoirs in the Skookumchuck Formation and one sandstone reservoir in the Lincoln Creek Formation (fig. 63). Torrent Energy (2008) also reported preliminary testing of coal-gas contents ranging from about 15–86 scf per ton and averaging more than 50 scf per ton. Based on coal thickness, extent, rank, and gas content, the coalbed methane potential was estimated at more than 400 BCFG for the Chehalis Basin (Torrent Energy, 2008).

In the Coos Bay coal basin (figs. 2 and 24), the lower and upper parts of the Coaledo Formation contain a net thickness of subbituminous to high-volatile bituminous coal of more than 100 ft. Torrent Energy (2008) reported that desorbtion tests of these coals yielded gas contents ranging from 60 to 230 scf of gas per ton, averaging about 148 scf gas per ton. The gas has a methane content of about 99 percent. The coal beds have yielded permeabilities ranging from 4 to 15 mD and averaged about 8 mD (Smith, 2008). Eleven coalbed methane wells were drilled between 2005 and 2007, with five wells hydraulically fractured (fraced) and currently being production tested. The estimated total in-place coalbed gas is 1.2 trillion cubic feet (TCF) with a potential 400 BCF recoverable (Torrent Energy, 2008).

The Eocene Coalbed Gas AU currently has no producing gas fields. Because of the lack of well production data in this AU, the Fort Union Coalbed Methane AU (50330183) in the Wind River Basin, Wyoming (Johnson and others, 2007), was used as an analog to estimate total recovery for untested cells having potential for additions to reserves over the next 30 yr. The Eocene Coalbed Gas AU is producing gas from coalbeds.

The AU is given a geologic probability of 1.0 because there is sufficient evidence that the AU has adequate charge, reservoirs, traps, seals, and favorable geologic timing for an untested cell to contain the selected minimum of 0.02 BCFG (appendix C). The minimum, mode, and maximum number of acres with the potential for adding to reserves within the AU are 9,905,000, 11,095,000, and 12,205,000 acres, respectively (appendix C). The minimum, median, and maximum areas of the AU that are untested are all estimated at 100 percent (appendix C).

There are Eocene coals throughout the Eocene Coalbed Gas AU, with four geologic "sweet spot" areas: the Bellingham Basin (fig. 61), the southeastern Puget Lowland and foothills (fig. 62), the southernmost Puget Lowland and Centralia Basin area (fig. 63), and the Coos Bay Basin (fig. 24). The Bellingham Basin contains at least 15 coal beds ranging in thickness from 1 to 15 ft. Coalbed methane has been detected in several old exploration wells, and one coal sample was desorbed resulting in a yield of 100 scf per ton (Johnson and others, 1997).

The coalbed-gas sources in the southeastern Puget Lowland and foothills of the western Washington Cascade Range (fig. 62) are coals within the Puget Group, and the Renton, Carbonado, and Spiketon Formations (fig. 5). Net coal thickness in the Puget Group has a mean thickness of 90 ft (Vine, 1969). The Renton Formation contains at least 10 coal beds in the Tiger Mountain area (fig. 62), with a net thickness of at least 36 ft. The Carbonado Formation contains at least 16 coal beds, of which nine beds range from 2 to 8 ft thick. Exploration wells, some of which were subjected to extended production testing, contained coalbed gas (Pappajohn and Mitchell, 1991). Pappajohn and Mitchell (1991) reported desorbtion values ranging from 218 to 564 scf per ton, averaging 423 scf per ton (fig. 62).

In the southernmost Puget Lowland and Centralia Basin area of the Eocene Coalbed Gas AU, the Cowlitz, Skookumchuck, and Spencer Formations contain thick gas-bearing coals as much as 40 ft thick. Duncan Oil Company, Inc. (2002), reported that desorbtion tests on coals recovered from the Duncan NWCH 42–9A well as high as 86 scf per ton in the 40-ft-thick Blue coal bed. Torrent Energy (2008) also reported preliminary testing of coal gas contents averaging more than 50 scf per ton. Based on coal thickness, extent, rank, and gas content, the coalbed methane potential was estimated at more than 400 BCFG for the Chehalis Basin area (Torrent Energy, 2008).

In the Coos Bay Basin (fig. 24), the lower and upper parts of the Coaledo Formation contain a net thickness of coal of more than 100 ft (fig. 26). Torrent Energy (2008) reported desorbtion test results for these coals that yielded gas contents averaging about 148 scf gas per ton. The estimated total in-place coalbed gas is 1.2 TCF with a potential 400 BCF recoverable (Torrent Energy, 2008).

The four "sweet spots" within the Eocene Coalbed Gas AU account for about 2,500,000 acres (22.5 percent) of the total 11,095,000 acres of the AU, and this percentage of acres was used to estimate the maximum area that remains for untested cells in the AU (second page of appendix C).

The estimated minimum, mode, maximum, and calculated mean percentages of untested area within the AU that has potential for additions to reserves in the next 30 years is 1, 3.1, 22, and 8.7 percent, respectively (appendix C). A necessary condition to meet these estimates is that the total recovery per cell is equal to or greater than the minimum recovery per cell of 0.02 BCFG; it is likely that this amount of gas can be recovered from a majority of the untested cells in the AU.

As previously discussed, the AU contains a thick section of coal-bearing strata with a continuous gas resource that were deposited in depositional settings similar to the analog Fort Union Coalbed Methane AU in the Wind River Basin, Wyoming (Johnson and others, 2007).

The minimum, median, and maximum total recovery for untested cells having potential for additions to reserves in the next 30 yr are 0.02, 0.1, and 2 BCFG, respectively (appendix C). These values were modified from similar values used in the analog AU; for example, the median value of 0.1 BCFG was about the same median value of 0.08 for the analog AU (Johnson and others, 2007), based on the presence of wells with shows of coalbed methane. These estimates for the total recovery for untested cells within the Eocene Coalbed Gas AU, however, assume that future production would be significantly greater in the next 30 yr.

The assessed mean undiscovered volume in the Eocene Coalbed Gas AU is 1,489 BCF of unconventional (continuous) gas (table 2), which is 67 percent of the estimated mean total of 2,214 BCF of gas within the Western Oregon and Washington Province that is presumed to be trapped in Tertiary coals of western Oregon and Washington.

Summary

The USGS assessed undiscovered, technically recoverable, conventional oil and gas and continuous (unconventional) coalbed gas in the Western Oregon and Washington Province, which includes about 40,000 mi^2 of western Oregon and Washington (table 2), resulting in an estimated mean total of 2,214 BCFG and a mean of 15 MMBO. More than 67 percent of the total mean gas (1,489 BCFG) is contained within the hypothetical Eocene Coalbed Gas AU, which encompasses an area of more than 11 million acres. In this continuous AU, the Eocene coals, such as the coal-bearing Eocene Coaledo Formation, serve as both the source and reservoir rocks. The mean estimated volume of gas for the Western Oregon and Washington Conventional Gas AU is 454 BCFG, with an estimated mean size of the expected largest gas field of 85 BCFG. For the Tertiary Marine AU, the estimated mean volume of gas is 249 BCF, with an estimated mean size of the expected largest gas field of 101 BCFG. The assessed mean undiscovered volume of oil in the Tertiary Marine Gas AU is 15 MMBO with estimated means of 22 BCF associated gas and 1 MMBNGL. The mean size of the expected largest oil field is estimated at 9 MMBO.

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Appendix A. Input parameters for the Western Oregon and Washington Conventional Gas Assessment Unit (50040101), Cretaceous-Tertiary Composite Total Petroleum System, Western Oregon and Washington Province

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (Version 6, 9 April 2003)

IDENTIFICATION INFORMATION

Assessment Geologist:	Michael E. Brownfield	Date:	2/24/2009
Region:	North America	Number:	5
Province:	Western Oregon-Washington	Number:	5004
Total Petroleum System:	Cretaceous-Tertiary Composite TPS	Number:	500401
Assessment Unit:	Western Oregon and Washington Conventional Gas	Number:	50040101
Based on Data as of:			
Notes from Assessor:	This frontier gas assessment unit is defined over a large area where potential reservoir and source rocks are known or inferred to coexist, Mist gas field cumulative production - 65 BCF through 2008.		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall): **Gas**

What is the minimum accumulation size? 0.5 mmboe grown (3.0 bcfg)
(the smallest accumulation that has potential to be added to reserves)

No. of discovered accumulations exceeding minimum size: Oil: ____ Gas: **1**
Established (>13 accums.) ____ Frontier (1-13 accums.) **1** Hypothetical (no accums.) ____

Median size (grown) of discovered oil accumulations (mmbo):
1st 3rd ____ 2nd 3rd ____ 3rd 3rd ____
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd ____ 2nd 3rd ____ 3rd 3rd ____

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. ≥ minimum size:	**1.0**
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. ≥ minimum size:	**1.0**
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. ≥ minimum	**1.0**

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): **1.0**

UNDISCOVERED ACCUMULATIONS

No. of Undiscovered Accumulations: How many undiscovered accums. exist that are ≥ min. size?:
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum (>0)	NA	mode	NA	maximum	NA
Gas Accumulations:	minimum (>0)	**1**	mode	**8**	maximum	**70**

Sizes of Undiscovered Accumulations: What are the sizes (**grown**) of the above accums?:
(variations in the sizes of undiscovered accumulations)

Oil in Oil Accumulations (m	minimum	NA	median	NA	maximum	NA
Gas in Gas Accumulations	minimum	**3**	median	**10**	maximum	**300**

AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)	NA	NA	NA
NGL/gas ratio (bngl/mmcfg)	NA	NA	NA

Gas Accumulations:	minimum	mode	maximum
Liquids/gas ratio (bliq/mmcfg)	0	2	4
Oil/gas ratio (bo/mmcfg)	NA	NA	NA

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS

(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	mode	maximum
API gravity (degrees)	NA	NA	NA
Sulfur content of oil (%)	NA	NA	NA
Depth (m) of water (if applicable)	NA	NA	NA

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	NA	NA	NA	NA	NA

Gas Accumulations:	minimum	mode	maximum
Inert gas content (%)	0.1	3.8	6
CO_2 content (%)	0	0.002	0.02
Hydrogen-sulfide content (%)	0	0	0
Depth (m) of water (if applicable)	0	50	200

		minimum	F75	mode	F25	maximum
Drilling Dep	(m)	305		1,220		5,490
	(ft)	1,000		4,000		18,000

Appendix B. Input Parameters for the Tertiary Marine Gas Assessment Unit (50040201), Tertiary Marine Total Petroleum System, Western Oregon and Washington Province

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (Version 6, 9 April 2003)

IDENTIFICATION INFORMATION

Assessment Geologist:	Michael E. Brownfield	Date:	2/24/2009
Region:	North America	Number:	5
Province:	Western Oregon-Washington	Number:	5004
Total Petroleum System:	Tertiary Marine	Number:	500402
Assessment Unit:	Tertiary Marine Gas	Number:	50040201
Based on Data as of:			
Notes from Assessor:	This hypothetical gas assessment unit is defined over a large area where potential reservoir and marine source rocks are known or inferred to coexist, uncertainty in existence of adequate source and reservoir rocks and timing for hyrocarbon accumulation		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall) **Gas**

What is the minimum accumulation size? **0.5** mmboe grown (3 bcfg)
(the smallest accumulation that has potential to be added to reserves)

No. of discovered accumulations exceeding minimum size: Oil: 0 Gas: **0**
Established (>13 accums.) ____ Frontier (1-13 accums.) ____ Hypothetical (no accums **X**

Median size (grown) of discovered oil accumulations (mmbo):
1st 3rd ____ 2nd 3rd ____ 3rd 3rd ____
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd ____ 2nd 3rd ____ 3rd 3rd ____

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. ≥ minimum size:	**1.0**
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. ≥ minimum size	**1.0**
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. ≥ minimum	**1.0**

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): **1.0**

UNDISCOVERED ACCUMULATIONS

No. of Undiscovered Accumulations: How many undiscovered accums. exist that are ≥ min. size?:
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum (>0)	**1**	mode	**2**	maximum	**10**
Gas Accumulations:	minimum (>0)	**1**	mode	**5**	maximum	**30**

Sizes of Undiscovered Accumulations: What are the sizes (**grown**) of the above accums?:
(variations in the sizes of undiscovered accumulations)

Oil in Oil Accumulations (n	minimum	**0.5**	median	**1.3**	maximum	**130**
Gas in Gas Accumulations	minimum	**3**	median	**8**	maximum	**800**

AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)	**750**	**1,500**	**2,250**
NGL/gas ratio (bngl/mmcfg)	**25**	**50**	**75**

Gas Accumulations:	minimum	mode	maximum
Liquids/gas ratio (bliq/mmcfg)	**12**	**25**	**38**
Oil/gas ratio (bo/mmcfg)	**NA**	**NA**	**NA**

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS

(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	mode	maximum
API gravity (degrees)	25	38	50
Sulfur content of oil (%)	0	0.3	1.5
Depth (m) of water (if applicable)	0	50	200

		minimum	F75	mode	F25	maximum
Drilling Dep	(m)	305		1,220		3,100
	(ft)	1,000		4,000		10,000

Gas Accumulations:	minimum	mode	maximum
Inert gas content (%)	0	2	10
CO_2 content (%)	0	1.5	10
Hydrogen-sulfide content (%)	0	0.5	3.5
Depth (m) of water (if applicable)	0	50	200

		minimum	F75	mode	F25	maximum
Drilling Dep	(m)	305		2,600		6,100
	(ft)	1,000		8,500		20,000

Appendix C. Input Parameters for the Eocene Coalbed Gas Assessment Unit (50040381), Tertiary Coalbed Gas Total Petroleum System, Western Oregon and Washington Province

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)

IDENTIFICATION INFORMATION

Assessment Geologist:	Michael E. Brownfield	Date:	2/24/2009
Region:	North America	Number:	5
Province:	Western Oregon-Washington	Number:	5004
Total Petroleum System:	Tertiary Coalbed Gas	Number:	500403
Assessment Unit:	Eocene Coalbed Gas	Number:	50040381
Based on Data as of:			

Notes from Assessor: This hypothetical gas assessment unit is defined over a large area where thick coal-bearing intervals are known to exist at depths less than 6,000 ft. Coalbed methane has been observed in 4 areas within the AU. Analog: Fort Union Coalbed Methane (Wind River Basin).

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions **Gas**
What is the minimum total recovery per cell? **0.02** (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells: 30 11 wells have been drilled with 5 wells being tested in Coos Bay, OR
Number of tested cells with total recovery per cell ≥ minimum: 0
Established (discovered cells): ______ Hypothetical (no cells): **X**
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum.	**1.0**
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	**1.0**
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum.	**1.0**

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): **1.0**

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

calculated mean **11,095,000** minimum **9,905,000** mode **11,095,000** maximum **12,205,000**

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

calculated mean **100** minimum **40** mode **80** maximum **180**

uncertainty of mean: minimum **60** maximum **140**

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)

calculated mean **100** minimum **100** mode **100** maximum **100**

Assessment Unit (name, no.)
Eocene-Coalbed Gas (50040381)

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell > minimum; uncertainty of a fixed value)

calculated mean	minimum	mode	maximum
8.7	**1**	**3.1**	**22**

Geologic evidence for estimates:

There are Eocene age coals throughout this AU with 4 areas (Bellingham, Southeastern Puget Lowlands, Cowlitz–Spencer, and Coos Bay) that account for about 22.5 percent of the total assessment unit. These areas contain thick coals and coalbed methane is known to be present in all areas. Torrent Energy estimates that the Coos Bay area contains 1.2 TCF coal gas with about 580 BCF of gas at a depth less than 4,000 ft.

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean	minimum	median	maximum
0.15	**0.02**	**0.1**	**2**

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS
out unknown values)

	minimum	mode	maximum
Oil assessment unit:			
Gas/oil ratio (cfg/bo)	NA	NA	NA
NGL/gas ratio (bngl/mmcfg)	NA	NA	NA
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	0	0

Assessment Unit (name, no.)
Eocene-Coalbed Gas (50040381)

SELECTED ANCILLARY DATA FOR UNTESTED CELLS
(values are inherently variable)

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)	NA	NA	NA
Sulfur content of oil (%)	NA	NA	NA
Depth (m) of water (if applicable)	NA	NA	NA

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.01	0.30	2.00
CO_2 content (%)	0.01	1.80	8.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	850	950	1050
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
152		305		1,829

Drilling depth (ft)

minimum	F75	mode	F25	maximum
500		1,000		6,000

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	28	10	25	50

Historic success ratio, tested cells (%) ______ About 1/2 of Steve Roberts Fort Union Analogs used in the North Slope Assessment

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other)
2. Fraction of wells drilled that are typically stimulated
3. Predominant type of stimulation (none, frac, acid, other)
4. Fraction of wells drilled that are horizontal

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