# WESTERN OREGON–WASHINGTON PROVINCE (004)

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## INTRODUCTION

Province 4, Western Oregon and Washington, includes all of Oregon and Washington north of the Klamath Mountains and west of the approximate crest of the Cascade Range. It extends offshore to the 3-mile limit of State waters on the west and to the International Boundary in the Straits of Juan de Fuca on the north. The province measures about 490 mi in a north-south direction and 50-140 mi east-west, encompassing roughly 40,000 sq mi.

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## REGIONAL GEOLOGY

Rocks accreted during Mesozoic subduction crop out around the margins of the province in the North Cascades, San Juan Islands, and Klamath Mountains and probably underlie the eastern part of the province at depth. They comprise a wide array of rock type, including mafic volcanic rocks, ultramafic rocks, graywacke, mudstone, chert, and plutonic and metamorphic rocks and are 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 (Crescent Formation, Siletz River Volcanics), variously interpreted as an accreted seamount complex or a transtensional rift sequence. In the Olympic Peninsula of western Washington, the thick submarine basalt of the Crescent Formation is structurally underlain by an Eocene to Miocene subduction complex (Ozette and Hoh melanges) that record ongoing subduction through Cenozoic time. 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.

Deposition occurred in a range of settings including fluvial, fan-delta, delta, shallow-marine, continental-slope, and submarine fan environments. The lower part of this Cenozoic forearc sequence is interbedded with and intruded by Eocene volcanic rocks. The strata show a general pattern of progradation northward from a southern Klamath igneous and metamorphic source and westward from both volcanic source terranes in the Cascade Mountains and distant crystalline rocks in northeastern Washington, eastern Oregon, and Idaho. Eocene 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. During the Eocene, the region experienced deformation forced by oblique subduction along the continental margin, as well as extension and clockwise rotation of the Coast Range block. This Eocene deformation caused widespread and heterogeneous folding, faulting, uplift, and subsidence.

Oligocene strata generally record a westward progradation of the coastline, have a significant volcaniclastic component, and are not generally prospective. 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 southwestWashington continued to subside. In middle and late Miocene time, flood basalt of the Columbia River Basalt Group was erupted in eastern Washington and Oregon. Huge volumes of basalt surged repeatedly down the course of the Columbia River, ponding in the floor of the northern part of the Willamette Valley and continuing on to the 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 present-day 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, the rapid uplift of the Olympic Mountains, and both reverse and strike slip-faulting.

## CONVENTIONAL PLAYS

Conventional plays formally assessed in this province include the Bellingham Basin Gas Play (0401), the Southeastern Puget Lowland Gas Play (0402), the Puget Lowland Deep Gas Play (0403), the Tofino-Fuca Basin Gas Play (0404), the Western Washington Melange Play (0405), the Southwest Washington Miocene Sandstone Play (0406), the Cowlitz-Spencer Gas Play (0407), and the Southwestern Oregon Eocene Gas Play (0410). Another conventional play, notably the Astoria Play (0408) was not formally assessed because it were considered to have less than a 0.1 probability of a 6 BCFG accumulation. Four unconventional plays were assessed: the Willamette-Puget Sound Basin-Centered Gas Play (0412), a continuous-type deposit written by B.E. Law, and three coalbed gas plays written by S.Y. Johnson and D.D. Rice, Western Washington–Bellingham Basin (0450), Western Washington–Western Cascade Mountains (0451), and Western Washington–Southern Puget Lowlands (0452). Further discussion of coalbed gas plays, with references, may be found in the chapter by Rice, "Geologic framework and description of coalbed gas plays" elsewhere in this CD-ROM.

## EXPLORATION HISTORY

The province has been intermittently explored with only limited success. Despite the drilling of about 500 wells since the early 1900's and the presence of numerous gas and oil seeps and shows, commercial production has been established only at the Mist gas field, northwest of Portland (about 70 BCFG), discovered in 1979. Several dozen exploration wells drilled in the vicinity of Mist since its discovery have failed to find a new field. In coastal Oregon, a well drilled in 1957 near Ocean City in southwestern Washington produced 12,000 barrels of 39¡ API gravity, but production rates declined below commercial levels; none of the many other wells drilled in that area found commercial oil or gas. In the Willamette Valley, a number of gas shows have been reported in exploration wells, and one well produced gas for several months before flow rates dropped. In recent years, there have been a few exploration wells drilled in the Bellingham Basin area of northern Washington, and in the eastern Puget lowland of central Washington, but no discoveries have resulted. Although the most promising targets have been tested, there is still a very large volume of undrilled rock, and the subsurface geology is still poorly known.

# CONVENTIONAL PLAYS

## 0401. BELLINGHAM BASIN GAS PLAY (HYPOTHETICAL)

This hypothetical gas play is located in the Bellingham Basin of the northern Puget Lowland of Washington. The exploration premise is that gas has been generated from organic-rich Cretaceous(?) to Eocene rocks (mainly nonmarine) and that it has migrated into reservoirs in Eocene fluvial sandstones. Structural traps for reservoirs might include large folds or smaller fault blocks, and interbedded fine-grained rocks would provide seals. The gas play is bounded to the south by uplifted, folded strata of the Eocene Chuckanut Formation and to the east by an uplift of pre-Tertiary basement rocks on Sumas Mountain. To the west, the play extends into the Strait of Georgia and is bounded by folded Cretaceous rocks of the Cowichan fold-and-thrust belt. To the north (both onshore and offshore), the play extends into Canada. Only the U.S. portion of the play is being evaluated.

**Reservoirs:** Potential reservoirs are the lower and middle Eocene fluvial- and distributary- channel sandstone (arkosic arenite) bodies of the Chuckanut Formation (Johnson, 1984). Sandstone bodies range in thickness up to 200 ft, are commonly conglomeratic, and typically include thin (< 1 ft), discontinuous lenses of mudstone. Sandstone bodies are bounded by fine-grained strata (mudstone to very fine grained sandstone) of fluvial overbank origin. In samples from one recent well, porosity decreased with depth from 26 percent at 1,000 ft to less than 10 percent at 6,000 ft (Hurst, 1991). Permeable reservoir rock may be locally present down to 4,500 ft, but not across the entire play. Measured permeabilities range from less than 1 mD to 58 mD.

**Source rocks**: The most likely source rocks are Eocene nonmarine carbonaceous shales and coals of the Chuckanut and Huntingdon Formations. In the Birch Bay No. 1 well, coals and shales above 6,000 ft are reported to have both type III and IIB kerogens, and numerous rocks in this interval contain more than 6 percent TOC (Hurst, 1991). Rocks below 6,000 ft in the same well have type III kerogens and low TOC values. Vitrinite reflectance values of ~ 0.5-0.6 have been reported from depths of 1,700-7,600 ft in the basin. Reflectance in Chuckanut Formation exposures on the south flank of the Bellingham basin is 0.74 percent (Walsh and Lingley, 1991). Gases analyzed from seeps up old well casings are mainly thermogenic (Hurst, 1991).

**Timing and migration of hydrocarbons:** Maximum burial occurred in the late middle to early late Eocene, prior to late Eocene folding and associated uplift. Thus, the large anticlinal traps in the basin would have formed during and slightly later than peak hydrocarbon generation and migration.

**Traps:** Large anticlines form the most viable hydrocarbon traps. Hurst (1991) calculated 5,000 acres of structural closure on the anticline on which American Hunter sited their Birch Bay #1 well. Based on continuation of surface trends from the south, there should be three or four additional comparable anticlines in the basin subsurface. The basin is also cut by numerous high-angle faults. Using the Mist field (northwestern Oregon) as an analog, small structural traps adjacent to these faults are also possible traps. Interbedded, fine-grained, nonmarine rocks are the likely seals; the lenticularity of these units is responsible for some uncertainty in trap viability.

**Exploration status:** Approximately 19 wells with a total depth (TD) > 1,500 ft have been drilled on the U.S. side of this play since 1914. Of these, only seven wells had TD greater than 5,000 ft (deepest is 9,126 ft). In Canada, approximately eight additional wells deeper than 5,000 ft have been drilled (maximum TD is 14,789 ft). Most recently, American Hunter and partners drilled three U.S. wells (TD from 4,422 ft to 9,126 ft) between 1988 and 1991. Gas shows were reported from several sandstone bodies and from coal beds. American Hunter sold its interest in the play to other groups who are presently trying to generate investors for more drilling with a focus on the coalbed methane resource.

**Resource potential:** This play has been poorly to moderately (at best) explored. There is only minor information about rocks at depths greater than 5,000 ft. Based on existing knowledge, the best objectives for a conventional gas play are at depths of less than 5,000 ft, where source and reservoir rocks are each of marginal quality. There is high probability of adequate structural traps and seals.

Existing infrastructure is highly favorable. Pipelines bringing gas to the Pacific Northwest urban corridor from Alberta extend through the Bellingham Basin. Any Bellingham Basin gas production could reach markets economically. This factor alone might lead to continuing exploration for and exploitation of small gas accumulations.

### 0402. SOUTHEASTERN PUGET LOWLAND GAS PLAY (HYPOTHETICAL)

This hypothetical play is located in the eastern Puget Lowland of Washington. The exploration premise is that gas has been generated from Eocene marine mudstones or nonmarine carbonaceous shales and coals and has migrated into reservoirs in Eocene fluvial sandstones. Structural traps for reservoirs might include anticlines and fault blocks, and interbedded fine-grained rocks and (or) overlying volcanic rocks would provide seals. The play is about 20-25 mi wide and is elongate north-south, extending from Morton to the Seattle urban area. The play is bounded to the east by either faults that juxtapose the Eocene section with pre-Tertiary basement rocks or by a depositional boundary where Eocene sedimentary rocks dip below a thick cover of Eocene and younger volcanic rocks. To the northwest, the play is bounded by the approximate facies contact between upper middle to upper Eocene nonmarine rocks (potential reservoir rocks within the play) and marine rocks (west of the play). To the southwest, the play boundary approximates the location of a structural boundary that separates a thicker, mainly nonmarine, highly deformed upper middle to upper Eocene sequence from a thinner, mixed marine-nonmarine, less deformed upper middle to upper Eocene sequence.

**Reservoirs**: Middle to upper Eocene fluvial- and distributary-channel sandstone bodies of the undifferentiated Puget Group, the Tiger Mountain Formation, the Renton Formation, the Carbonado Formation, and the Spiketon Formation (Buckovic, 1979) are the target reservoirs. These sandstone bodies range in thickness from 10 ft to > 200 ft and are bounded by fine-grained floodplain deposits. Sandstones are typically arkosic. Meager data suggest that sandstones are "tight" in the eastern part of the play where rocks have been buried more deeply and subjected to higher geothermal gradients. Porosity and permeability increase to the west. Near Black Diamond, Wash., porosities from two cores (depths of 1,840 to 6,000 ft) range from 6 to 37 percent, and permeability ranges from 1 to 2,025 mD (unpub. industry data).

**Source rocks:** There are two possible hydrocarbon source rocks: (1) Upper-middle to upper Eocene carbonaceous shale and coal of the undifferentiated Puget Group, and the Tiger Mountain, Renton, Carbonado, and Spiketon Formations. Surface outcrops and samples from shallow wells (< 2,000 ft) have $R_o$ values ranging from about 0.35 to 2.0 percent (Walsh and Lingley, 1991). Thermal maturity increases to the east and adjacent to intrusives. Area-specific thermal-maturity data are available for the Tiger Mountain, Green River, Wilkeson-Carbonado, Morton Antiform, and eastern Chehalis Basin areas. Organic matter is type III and gas prone.

(2) Lower to middle Eocene marine mudstones (Johnson, 1992, Stanley and others, 1994). These rocks are exposed only on Tiger Mountain, east of Seattle, where they are assigned to the Raging River Formation, but they are inferred to underlie a significant portion of the Puget Lowland and may have been penetrated in one borehole

(Alderwood No. 1). At Tiger Mountain, surface $R_o$ varies from 1.18 to 4.01 percent, and is 1.96 percent at 1,633 ft in one well. $T_{max}$ ranges from about 509¡-542¡C in outcrop and the shallow subsurface. TOC in these samples is as high as 0.8-1.1 percent. This remnant organic mater is an indication that rocks may have once been more organic rich and capable of generating hydrocarbons. Organic matter is type III and gas is the expected hydrocarbon type, but several oil shows have been reported from wildcat wells in the play area.

**Timing and migration of hydrocarbons:** Maximum burial occurred in the late Eocene to Oligocene, just prior to Miocene folding and associated uplift. However, regional heat flow was elevated with the onset of Cascades volcanism in the Oligocene and early Miocene. Thus, maximum heating and thermal maturation may postdate maximum burial. Structural traps in the play area probably formed during and slightly later than peak hydrocarbon generation.

**Traps:** Small anticlines and fault blocks form the most viable hydrocarbon traps. Interbedded fine-grained rocks (fluvial overbank deposits) and Oligocene and younger volcanic rocks provide possible seals. Traps might be present at depths ranging from 1,000 to 10,000 ft. The area is structurally complex and includes many faults and folds that have been active through the Neogene to the present and may have compromised the integrity of reservoirs and traps.

**Exploration status:** In 1983, Amoco drilled 11 stratigraphic tests in the area of this play (max TD = 2,780 ft). Since then, three exploratory wells have been drilled: (1) Voyager Petroleum, 1983, TD = 7,270 ft; (2) LB Petroleum, Inc., 1985, TD = 4,872 ft; (3) Meridian Oil Co., 1989, TD = 8,271 ft. The deepest well (TD = 12,920) in the play was drilled in 1963. Since 1985, approximately 11 coalbed methane wells have been drilled (max TD = 4,600 ft) in the play area; however, no production has resulted from this effort.

**Resource potential:** In the most favorable scenario, gas generated from source rocks in the eastern, more thermally mature, part of this play has migrated westward to the best reservoir rocks in the western part of the play. There are good reservoir rocks in the western part of the play; however, the history of Neogene tectonism and uplift may severely limit both longer distance migration and the integrity of traps. The structural complexity also makes exploration difficult. If traps for gas are present, they are probably small (6-20 BCFG) and will be hard to find.

**0403. PUGET LOWLAND DEEP GAS PLAY** (HYPOTHETICAL)

This hypothetical play is located in the eastern Puget Lowland of Washington. The exploration premise is that gas has been generated from deeply buried Eocene marine mudstone and has migrated into interbedded shelf or turbidite sandstone reservoirs. Structural traps for reservoirs might include anticlines and fault blocks, and interbedded fine-grained rocks and (or) volcanic rocks would provide seals. The play is about 25-30 miles wide and is elongate north-south, extending from Morton, Wash. to northern Whidbey Island, Wash. The play is bounded to the east and north either by faults that juxtapose the Eocene section with pre-Tertiary basement rocks or by a depositional boundary where Eocene sedimentary rocks dip below a thick cover of Eocene and younger volcanic rocks. The southwest boundary lies a few kilometers west of an early to early middle Eocene facies change; thick sequences of marine strata to the east are juxtaposed with marine basalt to the west. Structural uplifts cored by Eocene marine basalt bound the play to the northwest

**Reservoirs:** Lower to middle Eocene marine sandstone of the Raging River Formation (Johnson, 1992) and correlative unnamed rocks are the target reservoirs. Sandstone in the Raging River Formation is lithic rich and has virtually no porosity or permeability. There is no available data on correlative deeply buried units in the play area; however, based on regional paleogeographic patterns (e.g., Johnson, 1985, 1992), there should be both arkosic and lithic sandstones in these units. Although the probability is low, the reservoir properties of the arkosic sandstone bodies might be suitable for conventional gas reservoirs. It is also possible that the arkosic and lithic sandstones could serve as reservoirs for "basin-centered" unconventional gas accumulations.

**Source rocks:** Source rocks are inferred to be lower to middle Eocene marine mudstones (Johnson, 1992; Stanley and others, 1994). These rocks are exposed only on Tiger Mountain, east of Seattle, where they are assigned to the Raging River Formation, but they are inferred to underlie a significant portion of the Puget Lowland and may have been penetrated in one borehole (Alderwood No. 1). At Tiger Mountain, surface $R_O$ varies from 1.18 to 4.01 percent, and is 1.96 percent at 1,633 ft in one well. $T_{max}$ ranges from about 509¡-542¡C in outcrop and the shallow subsurface. TOC in these samples is as high as 0.8-1.1 percent. This remnant organic mater is an indication that rocks may have once been more organic rich and capable of generating hydrocarbons. Organic matter is type III, and gas is the expected hydrocarbon type, but several oil shows have been reported from wildcat wells in the play area.

**Timing and migration of hydrocarbons:** Maximum burial occurred in the late Eocene to Oligocene, just prior to Miocene folding and associated uplift. However, regional heat flow was elevated with the onset of Cascades volcanism in the Oligocene and early Miocene. Thus, maximum heating and thermal maturation may postdate maximum burial. Structural traps in the play area probably formed during and slightly later than peak hydrocarbon generation.

**Traps:** Small anticlines and fault blocks form the most viable hydrocarbon traps. Interbedded fine-grained rocks (marine and nonmarine) and Oligocene and younger volcanic rocks provide possible seals. Traps might be present at depths ranging from 2,000 to 20,000 ft. The area is structurally complex and includes many faults and folds that have been active through the Neogene to the present and may have compromised the integrity of reservoirs and traps.

**Exploration status:** Approximately 40 wells with TD > 3,000 ft have been drilled in the play area (includes 2 wells > 10,000 ft and approximately 17 wells between 5,000 and 10,000 ft), but perhaps only one well has penetrated the top of the deeply buried prospective section. In the last 10 years, activity in the play area has emphasized a possible coalbed methane resource. Department of Energy (DOE) recently supported acquisition of a large seismic database for the purpose of delineating a large conductive anomaly in the Cascade foothills that probably represents the Eocene marine rocks that are the inferred source and reservoir for this play (Stanley and others, 1992; Krehbiel, 1993). Following up this DOE-supported project, Hunt Oil has leased large tracts of land and is looking for partners to drill a deep well near Morton, Wash. (southern end of play). Otherwise, there is no known activity.

**Resource potential:** The viability of this play is dependent on the hypothesis that (1) marine source rocks underlie a large part of the Puget Lowlands, (2) these marine rocks include both source and reservoir beds, (3) there has been a favorable migration history, and (4) traps and seals have been preserved in a structurally complex setting. Given the uncertainties associated with each factor, this play is considered quite risky. Given the structural complexity, exploration for these accumulations should be difficult.

### 0404. TOFINO-FUCA BASIN GAS PLAY (HYPOTHETICAL)

This hypothetical gas play is located in the Tofino-Fuca Basin on the northern Olympic Peninsula of Washington. The exploration premise is that gas has been generated from Eocene strata buried in the deepest part of the basin or from Eocene melange in an underlying structural plate and has migrated either updip (deep basinal sources) or up basement fault zones (underplated sources) into Eocene turbidite sandstone reservoirs. Traps are most likely stratigraphic (buried pinchouts of turbidite sandstones), but small structural traps (fault-block traps and small anticlinal traps) are also possible. The Tofino-Fuca Basin Gas Play is bounded to the south by basement outcrops of the volcanic Crescent Formation, to the north by the international boundary with Canada in the Strait of Juan de Fuca, and to the west by the 3-mi limit of State lands in the Pacific Ocean. To the east, the play is bounded by the north-trending Discovery Bay Fault Zone, which disrupts the stratigraphic sequence.

**Reservoirs:** Upper middle Eocene to Oligocene turbidite sandstones (lithic arkosic to quartzo-feldspathic) of the Twin River Group (including the Hoko River, Makah, and Pysht Formations) are the target reservoirs (Snavely and others, 1980; Niem and Snavely, 1991). These sandstones form composite units that are as thick as 400 ft; individual sandstone beds range up to about 40 ft in thickness. Sandstone beds and units are bounded by marine mudstones. Proportion and thickness of sandstone decreases to the east. Meager data suggest porosity and permeability data may be as high as 20.4-24.6 percent and 2-657 mD, respectively, in the best potential reservoir rocks.

**Source rocks**: There are two possible source rocks for this play: (1) Eocene marine mudstones located downdip in the deepest part of the basin. TOC in these rocks (from surface exposures and one well) is typically between about 0.4 and 1.2 percent. Organic matter is type III and gas prone. Vitrinite reflectance for surface and well samples (to 8,400 ft) ranges from about 0.4 to 0.5 percent, however these rocks are buried downdip at depths to about 25,000 ft, where their thermal maturity would be greater.

(2) Marine mudstones in Eocene melange (or broken formation) in a structural plate that underlies the Tofino-Fuca Basin (Snavely and Kvenvolden, 1989). TOC in these rocks is typically 0.4 to 0.9 percent. Organic matter is type III and gas prone. Vitrinite reflectance of surface samples typically ranges from about 0.35 to 1.3 percent.

There are at least three seeps of thermogenic gas in the area of the play, indicating that source rocks have reached maturity and produced hydrocarbons. One seep was crudely gaged at a flow rate of 20,000 cf/day of methane (Lingley, 1986).

**Timing and migration of hydrocarbons:** Peak migration probably occurred in the early and middle Miocene, during maximum burial of both Tofino-Fuca basinal strata and the melange in the structurally lower thrust plate.

**Traps:** Possible stratigraphic traps include buried pinchouts of turbidite sandstones (channels and lobes); however, many of the possible reservoir bodies have been breached by erosion on the homoclinal flank of the basin. Structural traps are few and small and might occur along faults or as minor closure on faulted anticlines. Interbedded marine mudstone forms seals.

**Exploration status:** Nine wells with TD > 2,740 ft have been drilled in this play between 1948 and 1986. The two most recent wells include the 1986 Twin River Oil and Gas State No. 1-30 well (TD = 6,571 ft) and the 1982 Fairview Oil and Gas No. 1 well (TD = 7,158 ft). There is no known active exploration in the area of this play.

**Resource potential:** The presence of thermogenic gas seeps clearly indicates a viable source rock for the play. The presence of suitable reservoirs and traps is less certain, significantly downgrading the potential of this play.

### 0405. WESTERN WASHINGTON MELANGE PLAY (HYPOTHETICAL)

This hypothetical play is located along most of the Pacific Coast of Washington. The exploration premise is that oil and gas have been generated from organic-rich mudstones in Eocene to upper middle Miocene melange (broken formation) and has migrated into sandstone reservoirs in coherent structural blocks within the melange. To the north, south, and southeast, the play is bounded by a structural contact between the melange and Eocene marine volcanic rocks of the Crescent Formation. On the Olympic Peninsula, the eastern limit of the play is approximately at a location where low-grade metamorphism of the melange becomes more pervasive. To the west, the play extends to the 3-mi limit of State waters.

**Reservoirs:** Turbidite sandstone beds within coherent structural blocks in the Eocene to upper middle Miocene Ozette and Hoh Melange (or broken formation) are the inferred reservoir rocks. Based on log analysis, Palmer and Lingley (1989) suggest that sandstone units range from 10 to 100 ft in thickness, with a mean of about 34 ft. Thicker sandstone units probably include fine-grained interbeds or drapes and are heterogeneous. Most sandstones have porosities less than 25 percent and permeabilities less than 100 mD (Palmer and Lingley, 1989).

**Source rocks:** Eocene to upper middle Miocene marine mudstone in Ozette and Hoh melange are the inferred hydrocarbon source rock. The thickness of source-rock units is impossible to determine because of internal structural complexity within these units; however, melange is inferred to extend down to the top of the down-going Juan de

Fuca Plate, about 50,000-60,000 ft. Surface and well samples have relatively low TOC (typically 0.5 to 1.0 percent) and type III organic matter (Snavely and Kvenvolden, 1989). Although gas is the expected hydrocarbon type, drilling records report numerous oil shows and approximately 12,000 barrels of oil were produced from the Hoh melange in one well from 1957 to 1961 (McFarland, 1983; Palmer and Lingley, 1989). Thus, oil-prone source rocks at depth are expected. Both oil and gas seeps occur within the play area. Thermal maturity in possible source rocks varies significantly, probably in response to structural disruption. In the Ocean City, Washington area, rocks at depths of as much as 6,000 ft have typical $R_O \cong 0.6$ percent, however, in outcrops about 25 km to the north, $R_O$ in correlative rocks is generally between 1.0 and 1.5 percent.

**Timing and migration of hydrocarbons:** Migration in this complex setting has probably occurred continuously since the Oligocene as marine sedimentary rocks of Eocene and younger age were progressively underplated beneath the continental margin. Upward and westward migration of hydrocarbons along faults within the melange seems likely (Snavely and Kvenvolden, 1989; Palmer and Lingley, 1989).

**Traps:** There is almost certainly a variety of trap types within the structurally complex melange that are associated with fault blocks, anticlines, diapirs, and stratigraphic pinchouts or unconformities. Given the structural complexity of the melange, individual traps are probably very small (< 1,000 acres). Fine-grained rocks within the melange provide the seal, which is inferred to be far more viable for oil than for gas. The uniformly complex structural style across the play area suggests that traps are equally likely (or unlikely) in any part of the play. Similarly, the traps might occur at depths ranging from about 2,000 ft to about 23,000 ft, the depth at which gas should disappear, given geothermal gradients of about 1.5¡F/100 ft.

**Exploration status:** There is no known ongoing exploration in this play. About 80 exploration wells have been drilled in the area of this play since the early 1900's, 43 to depths greater than 3,000 ft. The last major exploration effort in this play ended in the late 1960's following drilling by Shell and Pan American on the adjacent continental shelf.

**Resource potential:** This play has limited potential. Reservoir quality and trap/seal integrity are the major limiting factors. Because of the complex structural style and poor outcrop, exploration is extremely difficult. Moreover, the small anticipated size of traps and reservoirs may discourage explorationists.

## 0406. SOUTHWEST WASHINGTON MIOCENE SANDSTONE PLAY (HYPOTHETICAL)

This play is located in the Grays Harbor Basin area of southwest Washington. The exploration premise is that oil and gas have been generated from organic-rich mudstones in Eocene to upper middle Miocene melange and have migrated upward into porous and permeable shallow marine sandstone of the Miocene Montesano and (or) Astoria Formation. Structural traps for reservoirs could include small anticlines and fault blocks. Overlying fine-grained rocks (if present) would provide the most viable seals. The play has an irregular shape that is defined by the presence of Miocene shallow-marine rocks in a structurally restricted area (Grays Harbor Basin) between the Olympic Mountains to the north, the Black Hill-Doty Hills uplift to the east, and the Willapa Hills to the south. To the west, the play extends to the 3-mi limit of State waters.

**Reservoirs:** Miocene shallow marine and deltaic sandstones of the Montesano Formation (western part of play) and Astoria Formation and lower Montesano Formation (eastern part of play) are the target reservoirs. In the west-central part of the play (Ocean City, Washington area), sandstone in the Montesano Formation has a maximum thickness of about 600 ft (Palmer and Lingley, 1989). In the eastern part of the play, several 100-ft-thick sandstone beds occur in both the Astoria and Montesano Formations (Bigelow, 1987). The overall proportion of sandstone in the Montesano and Astoria Formations decreases to the west. Sandstone units are bounded by marine mudstone. Montesano Formation sandstones typically have porosities > 20 percent and permeabilities ranging from 2 to 2,000 mD (Palmer and Lingley, 1989). There are no available porosity and permeability data for the Astoria Formation in this play, but sandstone outcrops are very friable, and values similar to those of the Montesano Formation are inferred.

**Source rocks:** Eocene to upper middle Miocene marine mudstone in Ozette and Hoh melange are the inferred hydrocarbon source rock. The thickness of source-rock units is impossible to determine because of internal structural complexity within these units; however, melange is inferred to extend down to the top of the down-going Juan de Fuca plate, about 50,000-60,000 ft. Surface and well samples have relatively low TOC (typically 0.5 to 1.0 percent) and type III organic matter (Snavely and Kvenvolden, 1989). Although gas is the expected hydrocarbon type, drilling records report numerous oil shows, and approximately 12,000 barrels of oil were produced from the Hoh melange in one well from 1957 to 1961 (McFarland, 1983; Palmer and Lingley, 1989). Thus, oil-prone source rocks at depth are expected at depth. Thermal maturity in possible source rocks varies significantly, probably in response to structural disruption. In the Ocean City, Washington area, rocks at depths of as much as 6,000 ft have typical $R_O \cong 0.6$ percent, however, in outcrops about 25 km to the north, $R_O$ in correlative rocks is generally between 1.0 and 1.5 percent.

**Timing and migration of hydrocarbons:** Migration has occurred from the late Miocene (after deposition of reservoir rocks) to the present. Westward migration along east-dipping thrust faults within the melange source rocks seems likely (Snavely and Kvenvolden, 1989). In the western part of the area, reservoir rocks directly overlie source rocks, and migration is straightforward. Migration in the eastern part of the area is more difficult because hydrocarbons must migrate through an Eocene to Oligocene section of volcanic and sedimentary rocks to reach Miocene sandstone reservoirs.

**Traps:** Small anticlinal traps that are either associated with faults (thrust, strike-slip) or with mudstone diapirs in the underlying melange are the most likely traps (Palmer and Lingley, 1989). Up-dip stratigraphic pinchouts within the Montesano Formation are less likely traps. Upper Miocene to Pliocene marine mudstones (in the upper part of and above the Montesano Formation) form possible seals. Target reservoir sandstone units occur at depths of about 1,000 to 3,200 ft. Closure on anticlinal traps cannot be demonstrated with available data and, if present, is probably no more than 1,000 acres. Trap/seal integrity is regarded as marginally viable for oil accumulation and nonviable for gas accumulation.

**Exploration status:** There is no known ongoing exploration in this play. About 70 wildcat wells have been drilled in the area of this play (max TD = 12,293 ft) since 1901, with the latest significant exploration effort occurring in the early 1980's.

**Resource potential:** This play has limited potential. Most oil and gas shows and the only (very minor) hydrocarbon production in this geographic area has come from the underlying melange. Evidence from shows and drillstem tests indicate there has been some hydrocarbon migration through Miocene sandstone (Palmer and Lingley, 1989). Therefore, the overlying seals may have been breached. There is clearly source and reservoir rock for this play. Trap and seal integrity are the limiting factors, particularly for gas accumulations. Oil accumulations are more likely in the western part of the play (west of the Crescent Formation basement); gas accumulations are more likely in the eastern part of the play.

## 0407. COWLITZ-SPENCER GAS PLAY

The Cowlitz-Spencer Gas Play is a confirmed gas play located in the southern Puget Lowland, southwestern Coast Range of Washington, and the lower Columbia River and Willamette Valleys of Oregon. It is defined by the known or inferred limits of potential reservoir sandstones in the lower Columbia River area and the Willamette Valley, principally the Eocene Cowlitz and Spencer Formations. Gas is presumed to have been generated from Eocene marine mudstone, nonmarine carbonaceous mudstone, or coal and trapped in Eocene sandstone reservoirs in fault traps, or, less likely, anticlines of Eocene or Miocene age. The play has an irregular shape and includes portions of the Chehalis, Grays Harbor, Nehalem, Astoria, Tualatin, and Willamette Basins. Uplifts of Eocene volcanic rocks define the play boundary locally. The play is bounded to the east by volcanic rocks of the Cascade Range or tightly folded and faulted Eocene strata in the Cascade foothills. To the northwest, in the Grays Harbor Basin, and to the west, in the Astoria Basin, the play boundary is defined by a facies change from sandstone to mudstone.

Only structurally trapped accumulations have been found so far in the play, but stratigraphic or combination traps are a possibility.

**Reservoirs**: Shallow marine sandstones of the middle to upper Eocene Cowlitz and Spencer Formations are the most likely reservoir units in the southern part of the play. The reservoir for the only discovered field in the play is the Clark and Wilson sandstone member of the Cowlitz Formation; it has reported porosity of 25-36 percent and permeability of 20-7,000 mD (Alger, 1985). The Clark and Wilson sandstone is about 600 ft thick in the Mist gas field area and consists of fine- to medium-grained shallow marine sandstone and interbedded mudstone. Sandstone in the correlative Spencer Formation in the Willamette Valley has reported porosity of 32-41 percent and permeability of 184-4,510 mD (Schlicker, 1962); it becomes tuffaceous and deteriorates in reservoir quality to the east outside the play area. The sandy lower member of the Spencer is 700 to 1,400 ft thick in the west-central Willamette Valley. Farther north, the sandstone-rich part of the Spencer is about 200 ft thick and is interbedded with mudstone and coal. It is a friable, cross-bedded, nearshore or beach sandstone. Other possible but less likely reservoir units in the southern part of the play are sandstone members of the middle Eocene Yamhill Formation (e.g, "Clatskanie" sandstone in the lower Columbia River Valley ).

In the northern part of the play in southwest Washington, middle to late Eocene fluvial, shallow-marine, and submarine-fan(?) arkosic sandstone of the Skookumchuck and McIntosh Formations are potential reservoir rocks in addition to the Cowlitz (Armentrout and Suek, 1985; Niem and others, 1991). Sandstone in the Jackson Prairie gas storage wells in the Cowlitz Formation in the Chehalis Basin has porosities of 30 to 40 percent at depths of 1,500 to 3,000 ft and permeabilities as high as 8,500 mD. Turbidite sandstone in the western part of the play (McIntosh Formation) has porosities of 10-22 percent and permeabilities of less than 6.2 mD. Sandstone bodies that are potential reservoirs within these formations are as thick as about 100 ft.

**Source rocks:** Presumed source rocks are mudstone or coal facies of the Yamhill, Tyee, Cowlitz, or Spencer Formations. Surface samples of mudstone from the Cowlitz Formation yielded TOC of 1.07 percent TOC and Spencer Formation mudstone 4.48 percent (Law and others, 1984). Subsurface samples of potential source rocks in the Mist gas field area are lean (generally <1 percent TOC) except for lignitic coals, which have over 40 percent TOC. Samples of the Keasey Formation above the Cowlitz contain 0.18 to 0.91 percent TOC (Law and others, 1984).

Middle to late Eocene marine shale and (or) coaly/carbonaceous shaly facies of the McIntosh, Skookumchuck, and Cowlitz Formations are the inferred source rock (Armentrout and Suek, 1985; Niem and others, 1991) for undiscovered accumulations in the northern part of the play. Organic matter in these rocks is type III and gas prone. Coals sampled at the surface and in subsurface (down to 10,000 ft) are of lignite to sub-bituminous rank; $R_o$ is generally between ~0.35 and 0.6 but can be slightly higher. Cumulative coal thickness is > 100 ft. $R_o$ of marine mudstone at the surface and shallow (< 5,000 ft) subsurface is generally ~0.4 to 0.5 with typical TOC of 0.5 to 1.25 percent. Seismic data reveal the presence of inferred marine strata at depths of ~6,500-16,400 ft below the Chehalis Basin, providing another possible source rock. Enhanced maturation of source rocks has occurred adjacent to intrusive centers within or on the margins of the play area.

**Timing and migration of hydrocarbons**: Gas shows have been widely encountered in exploration wells, although the gas may be partly or mostly biogenic rather than thermogenic because it is dominantly methane and nitrogen (Stewart and others, 1989). The accumulation at Mist gas field, however, has been demonstrated to be at least partly of thermogenic origin (Armentrout and Suek, 1985; Alger, 1985; Stormberg, 1992), and traces of ethane and heavier compounds are present in gas shows and tests in a few wells in the play outside of the Mist field (0.54 percent to 9 percent ethane and heavier hydrocarbons; analyses reported in Stewart and others, 1989). These occurrences indicate that a mature source rock is probably present at least locally, although it cannot be identified conclusively with available data. Sampled source rock candidates near Mist gas field are all immature except for samples from the Exxon GPE Federal Community well in the Nehalem Basin, in which $R_o$ values range from 0.56 at 7,910 ft to 1.64 at 10,770 ft (Stormbers, 1992). Surface samples of the Cowlitz and Keasey Formations yielded vitrinite reflectance values of 0.29-0.31 and $T_{max}$ values of 418¡C and 401¡C (Law and others, 1984), indicating that the presumed source section was not generally buried deeply enough to generate gas and may only have matured locally in areas of greater burial or adjacent to invasive flows of Columbia River Basalt.

Maximum burial of most of the presumed source section was achieved in Miocene time, so migration is most likely to have taken place then. If migration was a result of local heating by Columbia River Basalt Group intrusive flows, it likewise would have taken place in middle Miocene time.

**Traps**: Traps at Mist gas field are formed by up-dip closure against Eocene normal or oblique faults and sealed by overlying Cowlitz mudstone. They are typically small (1-8 BCFG). Undiscovered traps are probably mostly of this type, but stratigraphic traps formed by nearshore or deltaic sand bodies enclosed by mudstone could also be present. Although folding is not well developed, small folds with gently dipping limbs are potential traps (Armentrout and Suek, 1985; Niem and others, 1991). There has been ongoing tectonism in the area of this play throughout Cenozoic time, so fault-block traps could have formed before, during, or after peak hydrocarbon generation. Traps associated with good reservoir rocks probably occur between about 2,000 and 5,000 ft.

**Exploration status:** Mist gas field was discovered in 1979. Wells drilled in the area in the 1940's had indicated the presence of good reservoir rocks, but no new drilling took place between the 1940's and 1970's. In 1975, deliberate search for gas was begun, resulting eventually in the discovery well in 1979. Continued exploration and development revealed complex structure, with gas trapped in small pools of about 1.5 to 8 BCFG. Eleven pools were producing by 1984. Mist has an expected ultimate recovery of at least 70 BCFG (H.J. Meyer, Oregon Natural Gas Development Corporation, oral commun., 1994). More than 40 wells have been drilled in the general area surrounding Mist field, almost all of them since the discovery of Mist. About 30 exploration wells have been drilled in the entire area of the Willamette Valley, beginning in the early 1900's. A few shows of oil and numerous shows of gas, but no commercial discoveries, have resulted. One well in Linn County (American Quasar Hickey 9-12) produced 10 MMCF of gas (84 percent methane, 16 percent $N_2$, trace ethane) for 5 months in 1981. Oil and gas shows were also noted in several other wells in the Willamette Valley. Since the early 1960's, there has been only marginal exploration interest in the Washington part of this play, where about 20 wells have been drilled. Washington Natural Gas continues to operate a large natural gas storage facility in the Chehalis Basin.

**Resource potential:** The thermal maturity of source rocks is probably the largest limiting factor for the development of significant hydrocarbon accumulations in this play. The Mist field occurs along the Nehalem Arch, a structural high that appears unique within the play area and is probably the most important factor in the development of this large gas accumulation. There are large untested areas in the northern and southern parts of the play where accumulations as large as or larger than Mist could lie. The smaller scale structural setting at Mist, characterized by many fault-block traps, however, typifies the entire play area. Given this structural style, there should be many small gas accumulations within the play.

### 0408. ASTORIA PLAY (HYPOTHETICAL)

**Description:** The Astoria play is a hypothetical gas play defined by the known or inferred distribution of deltaic, nearshore or inner submarine fan channel-sandstone bodies in the Miocene Astoria Formation of northwesternmost Oregon. It has both structural and stratigraphic components.

**Reservoirs:** Three sandstone members of the lower and middle Miocene Astoria Formation constitute potential reservoirs. The deltaic and nearshore Angora Peak Member, inner submarine fan channel Youngs Bay Member, and shallow marine Wickiup Mountain Member (all from Niem and Niem, 1985) have reported porosities of 26-35 percent and permeabilities of 92-270 mD. The Angora Peak Member ranges in thickness from 70-100 ft to about 1,000 ft and consists of fine-grained massive feldspathic sandstone with subordinate crossbedded pebbly lithic sandstone and conglomerate and interbeds of carbonaceous siltstone and coal (Cooper, 1980). The Youngs Bay Member consists of thick-bedded, friable medium-to fine-grained sandstone lenses 200 to 1,100 ft thick. The Wickiup Mountain Member consists of 1,300 ft of fine-grained, locally friable sandstone (Niem and Niem, 1985). All of these units have significant lateral variation in thickness and reservoir quality.

**Source rocks:** Potential source rocks are moderately organic-rich mudstone in the lower and middle Miocene Astoria (Cannon Beach and Youngs Bay Members of Niem and Niem, 1985) and upper Eocene to lower Miocene Smuggler Cove Formations, reported to contain 0.65 - 2 percent TOC, dominantly type III (Niem and Niem, 1985). Mudstone in the Hoh-Ozette subduction complex at depth might be a source of gas or oil, but long-distance vertical migration would be required. Source rocks are probably mostly immature to marginally mature, but they are possibly locally mature where they were heated by middle and late Miocene intrusions of the Columbia River Basalt Group or in the offshore, where burial depths are greater. One Astoria sample yielded vitrinite reflectance of 0.65 percent and $T_{max}$ of 437¡C (Law and others, 1984). Mudstone of the Smuggler Cove Formation is locally mature to overmature ($R_o$ = 1.78-1.85 percent; Law and others, 1984) where it is intruded by Columbia River Basalt. Offshore, equivalents of postulated Miocene, Oligocene, and Eocene source rocks are buried to depths of 2-7,000 ft below sea bottom, as shown on one cross section by Niem and others (1992). Assuming a moderately low average geothermal gradient of about 1.5¡F/100 ft and a surface temperature of 35¡F (sea bottom), maximum temperature at the base of the source section would be about 140¡, making the likelihood of maturation by burial alone unlikely for the Oligocene-Miocene section unless there are thicker depocenters or areas with higher geothermal gradients elsewhere in the offshore.

**Timing and migration of hydrocarbons:** Maturation of source rocks by burial would have reached a maximum in late Miocene to Pliocene time. Maturation by basalt intrusion would have taken place in middle Miocene time, and in the subduction complex by early Miocene time. Migration pathways are uncertain, involving either vertical migration upward from the deeply buried subduction complex, local migration from source rocks heated by basalt, or lateral migration eastward from areas offshore where the section is thicker.

**Traps:** The most likely structural traps are fault traps adjacent to normal or oblique-slip faults of post-middle Miocene age. Structures that are exposed on land are breached and barren, but may serve as analogues for possible traps below the inner continental shelf. Steeply east-dipping reverse faults have also been inferred on the continental shelf (Niem and others, 1992), which might extend eastward into the State waters. Estimates of the sizes of either type of fault trap are speculative, but they may range from very small to perhaps larger than the Mist field, which is composed of several separate pools of up to about 10 BCFG each.

Inner submarine fan channels enclosed by mudstone are potential stratigraphic traps in the Youngs Bay Member of the Astoria Formation; their age would be lower to middle Miocene.

Interbedded mudstones enclosing sandstone lenses in the deltaic/nearshore facies of the Astoria Formation might also trap petroleum. Speculatively, a thick sill of middle Miocene basalt inferred from seismic on the inner continental shelf (Niem and others, 1992) might act as a seal if it is internally unfractured.

**Exploration status:** Only a few wells have been drilled in this play. A water well drilled in 1910 to 280 ft in inferred Youngs Bay Member "blew water 10 or 15 feet above the top of the casing and sustained a good flame" (Washburne, 1914, in Oregon Department of Geology and Mineral Industries, 1989). A wildcat (Lower Columbia Oil and Gas Company Brown No. 1) drilled to 4,808 ft in 1921 near the water well had gas shows and a trace of oil (Weaver, 1945). Two wells drilled in 1981 and 1983 (Oregon Natural Gas Development Johnson 33-33, TD 10,006 ft, and Patton 32-9, TD 10,159 ft) had gas shows; a Patton redrill to 3,917 ft apparently tested Astoria sandstone before being abandoned. In both of these wells, the primary objective was evidently below the Astoria, which is breached and eroded. About 20-25 mi offshore, the Shell P-075 and P-072 wells encountered only fine-grained facies of Astoria equivalents. The entire area of State waters is essentially unexplored, and no available well or seismic data provides any indication of its potential.

**Resource potential:** Although the presence of reservoir rocks in this play is established, the probability of adequate source rock richness and maturity must be considered to be fairly low (0.3) on the basis of available data. Likewise, the likelihood of adequate traps and seal is low (0.3) because the onshore part of the play is largely breached. Accordingly, the play is considered to have less than a 0.1 probability of a gas accumulation greater than 6 BCFG and was not formally assessed. Nevertheless, it cannot be dismissed as having no chance of significant gas accumulations, most likely in the State offshore waters or in a stratigraphic trap at depth onshore. If such an accumulation existed, it could be as big as several tens of BCFG, assuming a reservoir 200 ft thick and 1,000 acres in area. Smaller accumulations are much more likely.

### 0410. SOUTHWEST OREGON EOCENE GAS PLAY (HYPOTHETICAL)

This hypothetical gas play is coincident with the known and inferred distribution of deltaic, nearshore-marine, and continental-slope sandstone in the lower and middle

Eocene Umpqua and Tyee Formations in the southern Coast Range, and deltaic sandstone of the upper Eocene Coaledo Formation in the vicinity of Coos Bay in coastal southwestern Oregon. Possible source rocks are coal or carbonaceous mudstone interbedded in the Coaledo deltaic sequence, marine mudstone or coal in the Umpqua and Tyee Formations, or mudstone in Mesozoic melange that unconformably underlies but is thrust over Eocene strata in the southeast part of the play. The play has both structural and stratigraphic components.

**Reservoirs:** The mostly likely reservoir facies include coal-bearing nonmarine and deltaic sandstone of the White Tail Ridge Member and lithic conglomerate of the fan-deltaic and shelf- or slope-channel Bushnell Rock Member of the Umpqua Formation (Molenaar, 1985; Niem and others, 1992), arkosic shelf and slope sandstone facies of the Tyee Formation, shelf or deltaic sandstone in the Umpqua Formation, and channel, distributary-channel, and barrier-bar sandstone bodies of the Coaledo Formation. These units are variously of lower, middle, and upper Eocene age. Sandstone members of these units vary widely in thickness and reservoir quality. The few available porosity measurements in rocks of the Umpqua-Tyee sequence are generally low, averaging 7 percent to 17 percent as reported by Niem and Niem (1990). Permeability varies widely, ranging up to 154 mD in the most permeable sample measured, but is generally less than 1 mD to a few tens of millidarcies (Niem and Niem, 1990). Reported porosities in the Coaledo Formation are 18.3- 43.2 percent and permeability is 4.5-1788 mD (Newton, 1980). The Coaledo Formation, about 6,000 ft thick, is composed of three members. The lower and upper members (1,500-1,800 ft and 1,200 ft thick, respectively) are dominantly composed of micaceous sandstone interbedded with mudstone and coal.

**Source rocks:** Potential source rocks in the Umpqua-Tyee sequence include carbonaceous mudstone or coal in the Umpqua (White Tail Ridge, Coquille River, and Remote Members; TOC up to 50 percent according to Lillis and others, unpub. data) and Tyee Formations (TOC up to 43 percent according to Lillis and others, unpub. data; Law and others, 1984) and mudstone in underlying pre-Tertiary melange. 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 (Niem, 1990; Law and others, 1984). Subsurface samples have typical $R_o$ values of 0.45 -0.66 percent for samples in five wells (Niem, 1990; Pawlewicz, unpub. data). Gas seeps (mainly biogenic) and two oil seeps (Niem and Niem, 1990) suggest the presence of mature source rocks within the province; the oil seeps may be derived from sources in Mesozoic mudstones in Klamath melange terranes. Seeps of biogenic gas in deltaic facies of the White Tail Ridge Member of the Umpqua Formation are possibly related to degassing of interbedded coal (A.R. Niem, Oregon State University, written commun., 1993). Potential source rocks in the Coaledo Formation include coal and mudstone interbedded with the potential reservoir sandstones (TOC of about 1.45 percent in Coaledo mudstone according to Law and others, 1984) or other strata in the vicinity (Umpqua, Tyee, Elkton Formations), which have TOC's of about 0.4 percent to 1.35 percent; one Tyee coal has a TOC of 36.61 percent (Law and others, 1984). These units are all immature for gas in outcrop samples; however, with $R_o$ 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 1 contained 0.15 percent "heavy fraction" (Oregon Department of Geology and Mineral Industries, 1989) suggesting a thermogenic origin for some of the gas.

**Timing and migration of hydrocarbons:** Timing of hypothesized migration is uncertain. Source rocks on the southeast margin of the play may have matured during burial beneath Eocene thrusts or burial by younger Paleogene strata. Maximum burial was probably mostly achieved during Oligocene time. Therefore, widespread late Tertiary Neogene folds and faults are probably too young to trap petroleum, unless heating of the eastern margin of the play beneath late Eocene to Miocene volcanic rocks of the Cascade arc, along with local heating by intrusive bodies and hydrothermal fluids associated with volcanism, was adequate to mature source rocks not exposed in surface outcrops. In the Coos Bay area in the western part of the play, it is possible that correlative strata offshore might have had more burial in Neogene time than is observed onshore, and hydrocarbons could have migrated updip eastward into traps on the inner continental margin.

**Traps:** The most likely traps are early Tertiary folds and faults; stratigraphic traps are possible as well. Mudstone and impermeable sandstone interbedded with potential reservoir sandstones would seal the traps. Trap sizes are difficult to estimate; the evident marginal quality of the reservoir rocks and the lack of a good regional seal probably limits the size of accumulations that could be present in large anticlinal traps. Depths of most accumulations are likely to be less than about 8,000 ft based on the results of exploration drilling.

**Exploration status:** About 15 wells have been drilled in the Umpqua-Tyee sequence without success, several of them as recently as the 1980's. The Mobil Sutherlin Unit wildcat was drilled in 1979 to 13, 177 ft, and the Amoco Production Weyerhauser No. 1 was drilled in 1985 to 11,330 ft. In the Coos Bay area, about 12 wells have been drilled, many with gas and or oil shows or tests. Two wells on the Fat Elk anticline tested 750 and 1,000 MCFD at 1,600 ft and 1,170 ft, respectively (Newton, 1980). Two wells on the Westport Arch had gas shows at depths between 590 and 1,345 ft (Newton, 1980). The State waters inside the 3-mile limit, however, remain unexplored.

**Resource potential:** This play is considered to have potential for mostly relatively small gas accumulations. Largely inadequate maturity levels in most potential source rocks, marginal quality of potential reservoir rocks, and lack of a good regional seal suggest that large accumulations are unlikely. The most promising anticlines have been tested without a discovery, which also suggests that large accumulations are not likely. Fortuitous coincidence of locally good reservoir rocks, locally effective heating mechanisms, and effective seals cannot be expected to have occurred in very many places, even in such a relatively large play, so a small number of accumulations in the 6-12 BCFG range is considered most probable, although larger accumulations cannot be ruled out.

## UNCONVENTIONAL PLAYS

### *Continuous-Type Play*

***By B.E. Law***

***0412. WILLAMETTE-PUGET SOUND BASIN-CENTERED GAS PLAY (HYPOTHETICAL)***

The following characteristics are unique to basin-centered gas accumulations, a form of continuous-type accumulations: (1) regionally extensive accumulations that occupy the more central, deeper parts of basins, (2) absence of down dip water contacts, (3) overlain by a normally pressured transition zone containing gas and water, 4) abnormally overpressured or underpressured, (5) pressuring phase is gas, (6) produce little or no water, (7) low-permeability--commonly less than 0.1 mD, (8) contain thermogenic gas, (9) source of gas is from interbedded or adjacent rocks, 10) top of accumulations occurs at 0.75 to 1.0 percent vitrinite reflectance, (11) structural and stratigraphic trapping aspects are of secondary importance, and (12) the "seal" is a relative permeability barrier and is due to the presence of multiple fluid phases in low-permeability reservoirs. Because it is unlikely that all these characteristics can be identified in any single well, the most important characteristics to recognize are abnormal pressures (4), thermal maturity (10), and the abnormal pressure fluid phase (5).

The Willamette-Puget Sound Trough, located immediately west of the Cascade Mountains in Oregon and Washington, contains several smaller basins that include the Tualatin and Nehalem Basins in Oregon and the Chehalis, Tacoma, Seattle, and Everett Basins in Washington. These forearc basins are filled with Eocene and younger sedimentary rocks that were deposited in fluvial systems and may be as thick as 30,000 ft.

Only a few wells have been drilled in this play area that are deep enough to determine the presence of a basin-centered gas accumulation. Subsurface data from two wells, the Exxon, GPE Federal Com. No. 1 well, located in the Nehalem Basin of northwestern Oregon and the Phillips, State No. 1 well, located in the Tacoma Basin of west-central Washington, were drilled to depths of 11,287 ft and 12,920 ft, respectively. The top of abnormally high reservoir pressure occurs in these wells at depths of 8,000 to 9,600 feet, and the levels of thermal maturity at these depths are about 0.8 percent $R_o$. These relationships, in conjunction with the presence of interbedded coal beds and probable low-permeability reservoirs, indicate the presence of a basin-centered gas accumulation. However, because some deeply drilled wells in the area do not indicate the presence of a basin-centered gas accumulation and because of uncertainties regarding the geometry of the basins in the Willamette-Puget Sound Trough, the spatial and areal distribution of these basin-centered gas accumulations cannot be determined.

**Reservoirs:** Sandstone reservoirs in this play occur in Eocene and possibly older rocks. Borehole data indicate that gas-bearing reservoirs occur in an interval that is at least 3,300 ft thick. The bottom of the basin-centered gas accumulation is not known because the entire gas-bearing interval has not been drilled through. No porosity or permeability data are available from the reservoirs in the overpressured interval. Qualitative estimates of porosity and permeability are low.

**Source Rocks and Geochemistry:** In the absence of source rock analyses, the most likely sources of gas are the interbedded coal beds and carbonaceous shales. The levels of thermal maturity at the top of the gas accumulation are sufficiently high ( 0.8 percent $R_o$) to generate gas from available organic matter. Published and unpublished source rock analyses from various rock units in the Pacific Northwest indicate that nearly all of the organic matter is a type III kerogen and capable of generating mainly gas.

**Timing and Migration:** Because gas is generated within, or in close proximity to reservoirs in basin-centered gas accumulations, the temporal relationships between gas generation, migration, and development of a trap are not nearly as important as they are in conventional accumulations. It is uncertain when the reservoirs were charged with gas. Present-day temperatures at depths of 8,000-9,600 ft are about 130-150û F, too low to have achieved the present level of thermal maturity at that depth. Therefore, this area has experienced higher temperatures in the past than present-day temperatures.

**Traps and Seals:** See discussion in introduction to basin-centered gas accumulations.

**Depth of Occurrence:** The depth of reservoirs within the play area is uncertain. Limited data indicate that the top of the overpressured, basin-centered gas accumulation ranges from 8,000 to 9,600 ft. The bottom of the reservoirs is at least 13,000 ft. No wells have penetrated the entire basin-centered gas accumulation.

**Exploration Status:** The Willamette-Puget Sound Play is immaturely explored. Previous exploration activity in the play area has focused on more traditional structural and stratigraphic plays. This region has not been evaluated in the context of basin-centered gas accumulations.

## *COALBED GAS PLAYS*

***By S.Y. Johnson and D.D. Rice***

In western Washington, the target area for potential coalbed gas reserves is divided into three hypothetical plays based on geography and structure: (1) Western Washington–Bellingham Basin Play (0450), (2) Western Washington–Western Cascade Mountains Play (0451), and (3) Western Washington–Southern Puget Lowlands Play (0452). Further discussion of coalbed gas plays, with references, may be found in the chapter by Rice, "Geologic framework and description of coalbed gas plays" elsewhere in this CD-ROM.

### *0450. WESTERN WASHINGTON–BELLINGHAM BASIN PLAY (HYPOTHETICAL)*

This play involves coals of the Chuckanut Formation in Whatcom County, northwest Washington. The play is bounded to the south by uplifted Chuckanut strata, to the east by an uplift of pre-Tertiary basement rocks, and to the west by the Strait of Georgia. To the north (both onshore and offshore), the play extends into Canada. Only the U.S. portion of the play was evaluated. Four boreholes that could be broadly interpreted as coalbed gas wells have been drilled since 1986. The potential for reserves in the Bellingham Basin Play (0450) is considered fair, with low coal rank considered the main limiting factor.

### *0451. WESTERN WASHINGTON–WESTERN CASCADE MOUNTAINS PLAY (HYPOTHETICAL)*

This play involves coal beds in the structurally complex foothills of the Cascade Mountains in King, Pierce, Lewis, and Thurston Counties. Host rock units (the undifferentiated Puget Group and the Renton Formation, Carbonado Formation, and Spiketon Formations) are cut by numerous folds and faults. The play is bounded to the east by either faults that juxtapose the Eocene section with pre-Tertiary basement rocks, or by a depositional boundary where Eocene sedimentary rocks dip below a thick cover of Eocene and younger volcanic rocks. To the northwest, the play is bounded by the approximate facies contact between nonmarine rocks and marine rocks. To the southwest, the play boundary approximates the location of a structural boundary that separates a thicker, mainly nonmarine, highly deformed Eocene sequence from a thinner, mixed marine-nonmarine, less deformed Eocene sequence. Fifteen boreholes that could be broadly interpreted as coalbed gas wells have been drilled in the play since 1986. The potential for reserves in this play is considered fair, with structural complexity considered the main limiting factor.

### *0452. WESTERN WASHINGTON–SOUTHERN PUGET LOWLANDS PLAY (HYPOTHETICAL)*

The Southern Puget Lowlands Play (0452) involves coals of the Skookumchuck and Cowlitz Formations in Thurston, Lewis, and Cowlitz Counties of southwest Washington. The play is bounded to the east by volcanic rocks of the Cascade Range or tightly folded and faulted Eocene strata in the Cascade foothills, and to the south, west, and north by uplifts of Eocene volcanic rocks. No recent coalbed gas exploration has been accomplished in the area of this play. The potential for reserves in this play is considered fair to poor, with low coal rank considered the main limiting factor.

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