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Geologic Basis for Petroleum Resource Assessment of Onshore Western Oregon and Washington (Province 72)

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INTRODUCTION

Province 72 includes western Oregon and Washington from the Cascade Range westward to the three-mile limit offshore, and from the Strait of Juan de Fuca southward to the Klamath Mountains (fig. 1). The province is about 700 km (440 mi) long and 80-225 km (50-140 mi) wide, and covers about 96,900 km^2 (37,400 mi^2), of which about 26% (25,600 km^2 or 9,900 mi^2) is land owned by the Federal Government.

The province is geologically complex, and many aspects of its stratigraphy and structure are controversial. The main petroleum exploration objectives are in moderately deformed Tertiary sedimentary rocks, but the province also includes large surface exposures of igneous and metamorphic rocks with little or no hydrocarbon potential. More than 500 exploratory wells have been drilled in this area since the turn of the century (Braislin and others, 1971), resulting in the discovery of one commercial gas field of modest size, and no commercial oil fields. The main problems facing the explorationist in this region are (1) petroleum source rocks that generally are thermally immature and organically lean; (2) difficulties in finding porous and permeable reservoir rocks; and (3) complex structure, made difficult to resolve by thick vegetative cover, sparse well control, and locally poor seismic record quality. However, these problems are not insurmountable, as discussed later in this report.

The purpose of this report is to provide part of the geologic basis for a recently-completed estimate of undiscovered conventionally recoverable oil and natural gas resources in the United States (Mast and others, 1989). All of the information in this report came from published sources and from conversations with knowledgeable people; no new research results are presented here.

The geologic framework and petroleum potential of western Oregon and Washington have been the subject of numerous investigations, resulting in a voluminous body of literature. Recent reviews that were particularly useful to me (and also contain large bibliographies) include Armentrout and Suek (1985), Braislin and others (1971), Heller and others (1987), Johnson and others (1984), Molenaar (1985), Niem and Niem (1984, 1985), Olmstead (1989), Petroleum Information (1985), Snavely and others (1977), Snavely (1987), and Stewart and others (1989). The following brief and highly generalized discussions are based on much more detailed information in these and other reports.

GENERAL STRATIGRAPHIC AND STRUCTURAL SETTING

Much of western Oregon and Washington occupies the site of a deep sedimentary basin that is floored by Paleocene and lower Eocene oceanic basaltic crust, and contains as much as 7,600 m (25,000 ft) of early Eocene and younger sedimentary and volcanic rocks (fig. 2). From a petroleum point of view, the oceanic basalts are regarded as "economic basement"--that is, the top of the oceanic basalts is presumably the base of the potential hydrocarbon-bearing section represented by the overlying sedimentary and volcanic rocks.

The Paleocene and lower Eocene oceanic basalts are known as the Siletz River Volcanics and Roseburg Formation of Baldwin (1974) in Oregon, and as the Crescent Formation in Washington (figs. 3 and 4). These tholeiitic to alkalic basalts are more than 15,000 m (50,000 ft) thick on the Olympic Peninsula (Cady, 1975), but their thickness is unknown over most of the rest of the area. They are thought to represent oceanic ridge basalts and associated oceanic islands and seamounts that erupted during a period of rifting and extension along the western edge of the North American continental margin, and then collided with and accreted to the North American Plate about 50 Ma (Snavely, 1987).

Overlying the oceanic basalts is a pile of sedimentary and volcanic rocks that were deposited in a forearc setting during the last 50 Ma. The thickness of the pile is variable, with depocenters up to 7,600 m (25,000 ft) thick punctuated by thin areas that may represent ancient seamounts. The stratigraphy of the pile is complex, and varies from place to place (figs. 3 and 4). The sedimentary rocks consist mainly of sandstone, siltstone, mudstone, and conglomerate that were derived from both continental and volcanic provenances and deposited in a wide variety of depositional environments ranging from deep-sea fan to shallow-marine shelf, deltaic, and fluvial. In general, nonmarine facies on the east interfinger with marine facies on the west (Snavely and Wagner, 1963). The intercalated volcanic rocks exhibit a wide range of compositions and apparently were derived from several sources, including (1) subduction-related magmatism in the nearby Cascades volcanic arc, (2) local eruptive centers related to extensional episodes within the forearc basin (Snavely, 1987), and (3) invasive tongues of flood basalts that erupted on the Columbia River Plateau (Beeson and others, 1979).

The geologic history represented by these rocks is only broadly known, but is believed to have been controlled by episodes of extensional, convergent, and strike-slip tectonics between the North American plate and various plates of the Pacific Ocean basin (Snavely, 1987; Wells and others, 1984). Rifting and extension occurred about 60-55 Ma, resulting in formation of oceanic basaltic crust which then was accreted to the North American continent about 50 Ma (Snavely, 1987; Bukry and Snavely, 1988). The resulting forearc basin was subsequently filled by essentially continuous sedimentation punctuated by episodes of both extension and compression, which in turn were controlled by plate interactions along the continental margin that varied between oblique convergence and head-on subduction (Snavely, 1987). The Cascade Range has been active as a magmatic arc since about 42 Ma (Wells and others, 1984). Paleomagnetic studies indicate that parts of the area have undergone clockwise rotations about vertical axes of as much as 80° since the Paleocene, complicating paleogeographic reconstructions (Heller and others, 1987; Magill and Cox, 1980; Simpson and Cox, 1977; Wells and Heller, 1988; Wells, 1989). Along the western margin of the forearc basin, thick accretionary wedges of Ozette and Hoh melange and broken formation were created and thrust beneath the Siletz River and Crescent oceanic basalts; the melange and broken formation crop out onshore in a narrow strip along the west coast of the Olympic Peninsula (Snavely and Kvenvolden, 1989).

GENERAL PETROLEUM GEOLOGY

As noted above, the major petroleum exploration objectives in western Oregon and Washington are in the middle Eocene and younger sedimentary rocks which cover most of the province. However, certain parts of the province can be rejected outright as having no petroleum potential. These include areas where Paleocene and lower Eocene oceanic basalts of the Siletz River Volcanics and Crescent Formation are present in outcrop or very shallow subsurface; and the central Olympic Peninsula, where surface outcrops are mainly metamorphosed Tertiary sedimentary rocks generally regarded as having zero petroleum potential (Snavely and Wagner, 1980).

Exploration history

Exploration for petroleum in western Oregon and Washington apparently began about 1881, with reports of petroliferous "smell muds" and oil and gas seeps along the Washington coast (Armentrout and Suek, 1985). Drilling began about 1890 (Glover, 1936; McFarland, 1983), and more than 500 exploratory wells have been drilled since 1900 (Braislin and others, 1971). Only about 80 wells have penetrated deeper than 5,000 ft, and most of these were drilled before World War II (Petroleum Information, 1985). Thus, western Oregon and Washington is still regarded as a frontier exploration area.

Drilling activity in western Oregon and Washington has been sporadic. During the 1930's and 1950's, drilling by small operators found shows of oil and gas in the Eocene Puget Group on the Kummer anticline east of Tacoma (Anderson, 1959; McFarland, 1983). In this area, the Washington-California Oil and Gas Co.-Sound Cities Gas and Oil Co., Inc., Bobb No. 1 well allegedly produced gas and about 500 barrels of 24-26° API (American Petroleum Institute) gravity oil from a sand about 6 m (20 ft) thick at a depth of about 975 m (3,200 ft). However, this allegation could not be confirmed by the Washington State inspector who visited the drillsite (W.S. Lingley, Jr., Washington State Division of Geology and Earth Resources, written communication, November 26, 1990). Confirmed reports indicate that shows of paraffinic oil were found in the Phillips State No. 1 well east of Tacoma (Walsh and Lingley, 1990).

During the 1950's, several major oil companies entered the region with modern geological and geophysical techniques, resulting in several drilling programs. Several wells in the Ocean City area on the Washington coast (fig. 1) encountered good shows of oil and gas in the Oligocene to Miocene Hoh melange and broken formation of Snavely and Kvenvolden (1989). The best of these wells, the Sunshine Mining Co. Medina No. 1, produced about 12,000 barrels of 38.9° API gravity, paraffin-base oil from sheared siltstone reservoirs of middle Miocene age in the Hoh at 1,204-1,206 m (3,952-3,958 ft) (Braislin and others, 1971; Kvenvolden and others, 1989; McFarland, 1983; Rau and McFarland, 1982; Snavely and Kvenvolden, 1989; Wurden, 1959). This well was plugged and abandoned in 1962, however, because the fractured reservoirs were small and of low permeability, and because the montmorillonitic shales of the Hoh tended to flow and plug casing perforations (McFarland, 1983; Petroleum Information, 1985). On the northern Olympic Peninsula, near the Strait of Juan de Fuca, several wells have found gas shows but tight reservoirs in sandstones of the Eocene and Oligocene Twin River Group (Northwest Oil Report, 1986, 1987; McCaslin, 1986; McFarland, 1983; Thurston and others, 1987).

Several wells have been drilled near Coos Bay in southwestern Oregon (fig. 1) since the 1930's, finding strong shows of dry gas in sandstones of the coal-bearing Eocene Coaledo Formation, and minor shows of both oil and gas in rocks older than the Coaledo (Newton, 1980; Oil and Gas Journal, 1990a; Stewart and others, 1989; Webster, 1985). In the Willamette Valley (fig. 1), a number of wells have reported oil and gas shows (Deacon, 1962; Dignes and Woltz, 1981; Stewart and others, 1989). Subcommercial production of gas was obtained in 1981 by the American Quasar 9-12 Hickey, a Mobil farmout drilled in the Willamette Valley near Lebanon, Linn County, Oregon (fig. 1). This well tested 170,000 cubic feet of gas per day from sandstone in the Eocene Eugene Formation at 916-923 m (3,004-3,027 ft), and was touted briefly as a new field discovery before being plugged and abandoned (Dignes and Woltz, 1982; McCaslin, 1981; Stewart and others, 1989). Oil and gas shows have also been reported from surface seeps and from several wells drilled in the Tyee basin in the southern Oregon Coast Range; a detailed evaluation of the petroleum resources of this area is underway (Niem and Niem, 1990).

Mist gas field

Exploratory drilling in the Mist area of northwestern Oregon began in 1945 and led eventually to the discovery of the Mist gas field (fig. 1). The Mist field is located on a small, faulted, northwest-trending anticline about 70 km (45 mi) northwest of Portland. The field was discovered in 1979 (after several dry holes with shows of gas but no oil) by partners Reichhold Energy Corporation, Diamond Shamrock Corporation, and Northwest Natural Gas Company (Newton, 1979). Interestingly, while Reichhold and Diamond Shamrock were pursuing a commercial gas discovery, Northwest Natural Gas was more interested in finding a gas-storage site for pipeline gas (Blaisdell and Dignes, 1980; Olmstead, 1985). By the end of 1986 (the approximate time of the FLAP assessment) the field consisted of 14 wells producing from nearly as many pools, with a total cumulative production of 27.9 billion cubic feet of gas (Wermiel, 1987). By the end of 1989, the field consisted of 18 producing wells, with a total cumulative production of 38.4 billion cubic feet (Wermiel, 1990). Depleted gas pools at Mist have been used for gas storage since 1987 (Oil and Gas Journal, 1989). The geology of the field is described in detail by Bruer (1980), Alger (1985), and Armentrout and Suek (1985); a few high points are discussed below.

Gas in the Mist gas field is produced from sandstone reservoirs in the middle to upper Eocene (Narizian) Cowlitz Formation (Armentrout and Suek, 1985). The productive intervals occur at depths of 400-820 m (1300-2700 ft). Porosities range from 18% to 32%, averaging about 25%; permeabilities range from 19 md to more than 1,500 md, averaging about 200 md (Armentrout and Suek, 1985). The reservoir sandstones are well-sorted, quartzofeldspathic, and friable, with trough cross-stratification, ripple structures, bioturbation, shallow-marine ostracodes, and coalified (lignitic) plant fragments (Alger, 1985). Opinions vary as to the origin of the reservoir sands; they may have been deposited in nearshore, high-energy, wave-dominated shelf environments (Alger, 1985; Armentrout and Suek, 1985), or alternatively they may have accumulated on the current-swept floor of a narrow seaway analogous to the modern Strait of Juan de Fuca (Bruer, 1980).

The trapping conditions at Mist are complex and still under debate. Most of the gas pools appear to be in fault traps on a large anticlinal structure (figs. 5, 6, 7; Alger, 1985). However, at least one gas pool occurs in a shale-encased sandstone, a pure stratigraphic trap (Armentrout and Suek, 1985). Tuffaceous deep-water shales of the upper Cowlitz and Keasy Formations overlie the gas-producing reservoir sandstones and serve as impermeable sealing beds (Armentrout and Suek, 1985).

The source of the gas at Mist also is uncertain. The Mist gas is very dry and isotopically light; its composition suggests that it was thermally generated (Bruer, 1980; Armentrout and Suek, 1985). The shales surrounding the sandstone reservoirs at Mist have vitrinite reflectance values less than 0.4%, suggesting that the gas was not generated locally, but must have migrated into the area from zones of deeper burial and higher thermal maturity (Alger, 1985; Armentrout and Suek, 1985). A Lopatin plot (fig. 8) and organic geochemical data assembled by Armentrout and Suek (1985) suggest that the Mist gas was generated in organic-rich, marginal marine and deltaic shales and coals in a nearby depocenter; gas generation may have occurred during the Oligocene, when these rocks were buried to depths of about 3,350 m (11,000 ft). Gas generation may have been enhanced by local heating from upper Eocene and middle Miocene basalt intrusions (Niem and Niem, 1985, 1990), and migration of the gas may have been assisted by hot fluids expelled during emplacement of the intrusions (Summer and Verosub, 1987b).

While no oil has been reported from the Mist field, minor shows of oil and gas were reported from a well drilled 17 km (11 mi) southeast and downdip from Mist (Newton, 1988).

Petroleum source rocks

Fine-grained sedimentary rocks that could serve as potential hydrocarbon source rocks occur throughout western Oregon and Washington. Geochemical analyses of hundreds of surface and subsurface samples allow the following generalizations. (1) The organic matter in most samples is predominantly Type III and Type IV kerogen of terrestrial derivation, and has the potential of generating gas but little or no oil. (2) Total organic carbon (TOC) contents exhibit a wide range, from less than 0.5% for marine shales to more than 55% for coals; however, most samples are organically lean, exhibiting TOC values of less than 1%. (3) Thermal maturities are variable, but most samples have vitrinite reflectance values of less than 0.6%, indicating that they are immature to marginally mature with respect to the oil window (Armentrout and Suek, 1985; Grady, 1986; Law and others, 1984; Niem and Niem, 1990; Snavely and Kvenvolden, 1989; Sparks, 1980; Walsh and Lingley, 1990).

Higher levels of thermal maturity may occur in several settings, including: (1) near igneous intrusions where there may have been contact thermal metamorphism, or heating due to hydrothermal activity; (2) along faults and shear zones where there may have been frictional heating; (3) in certain areas, such as accretionary wedges, that may have been heated by subducting warm oceanic crust or hot fluids associated with subduction; and (4) in depocenters where the sedimentary pile is unusually thick, resulting in deep burial (Armentrout and Suek, 1985; Niem and Niem, 1985; Niem and others, 1990; Snavely, 1987; Snavely and Kvenvolden, 1989; Summer and Verosub, 1987a, b; Walsh and Lingley, 1990). Lopatin calculations by Armentrout and Suek (1985) suggest that 3,050 m (10,000 ft) of burial is the minimum for thermal generation of hydrocarbons in western Oregon and Washington, unless higher heat flow (e.g., from a nearby igneous intrusion) was encountered. High thermal gradients and related hydrocarbon generation may have occurred along the eastern side of the Willamette Valley during Oligocene and Miocene volcanism in the nearby Cascades (Armentrout and Suek, 1985). Thermally mature Paleogene rocks, apparently heated by Miocene igneous intrusions, occur in the eastern Puget Trough and Cascade foothills (Walsh and Lingley, 1990).

Specific examples of rocks identified as potential petroleum source rocks in publications and unpublished consulting reports include marine and nonmarine shales and coals in the Eocene Umpqua, Tyee, Yamhill, Cowlitz, Skookumchuck, Coaledo, Aldwell, Keasy, and Hamlet Formations, the Puget Group, and the Ozette melange and broken formation; the Eocene and Oligocene Alsea and Nestucca Formations and Twin Rivers Group; the Eocene to Miocene Smuggler Cove Formation; the Oligocene and Miocene Hoh melange and broken formation; and the Miocene Nye Mudstone and Astoria Formation (figs. 3, 4; Armentrout and Suek, 1985; Braislin and others, 1971; Law and others, 1984; Molenaar, 1985; Newton, 1980; Niem and Niem, 1985, 1990; Snavely and Kvenvolden, 1989; Snavely and others, 1977).

As noted above, the gas at Mist gas field is most likely thermogenic in origin, and may have been generated in organic-rich, marginal marine and deltaic shales and coals in a nearby depocenter (Armentrout and Suek, 1985); local heating by igneous intrusions may also have played a role (Niem and Niem, 1985, 1990; Niem and others, 1990). Gas and oil in the "smell muds" and seeps of the Washington coast, as well as in the wells near Ocean City, were apparently thermally generated in the Eocene Ozette melange and broken formation, and later migrated along thrust faults into fractured reservoirs of middle Miocene age in the Hoh melange and broken formation (Kvenvolden and others, 1989; Snavely and Kvenvolden, 1989).

Reservoir rocks

A major problem in petroleum exploration in western Oregon and Washington is the relative scarcity of porous and permeable reservoir rocks. Most of the literature on the sandstones of western Oregon and Washington focuses on their volcaniclastic origin and lack of reservoir potential (e.g., Armentrout and Suek, 1985; Burns and Ethridge, 1979; Chan, 1982, 1985; Galloway, 1974; Niem and Niem, 1990). Such sandstones generally make poor hydrocarbon reservoirs because the volcanic-lithic grains are chemically unstable, and during burial diagenesis are altered to clay minerals and zeolites that clog pore spaces.

The experience at Mist gas field, however, demonstrates that high-quality reservoir rocks are present at least locally in western Oregon and Washington. The reservoir sandstones in the Cowlitz Formation at Mist, as noted above, are composed mainly of quartz and feldspar with few or no volcanic-lithic grains; these "clean" sandstones are much less susceptible to diagenetically-formed, pore-filling authigenic minerals than are the more typical lithic-rich sandstones of western Oregon and Washington.

According to Armentrout and Suek (1985), the Cowlitz Formation sandstones at Mist were apparently deposited during middle to late Eocene time in shallow-marine and deltaic settings along a broad coastal plain and shelf extending from Coos Bay, Oregon, to Bellingham, Washington. The quartz and feldspar grains were apparently transported from the east by river systems draining plutonic-metamorphic terrains such as the Idaho batholith and the North Cascades. The lack of volcanic lithic grains in the Cowlitz sandstones is attributed to deposition in paleogeographic settings away from volcanic centers, under conditions of high energy that prevented deposition of fine-grained tuffaceous material with the quartzofeldspathic sandstones. In addition, deposition of Cowlitz sands may have occurred during a "volcanically quiet" period of time related to a westward shift of the subduction zone along the Oregon-Washington continental margin (Armentrout and Suek, 1985; Snavely and others, 1980).

The implication of the foregoing is that prediction of other reservoir-quality sands in western Oregon and Washington requires a precise understanding of provenance, paleogeography, paleotectonics, and volcanism. Armentrout and Suek (1985) propose that reservoir sands are most likely to be found where the provenance is continental, depositional environments are high-energy (e.g., channels in fluvial and deep-sea fan settings; wave-dominated shallow-marine settings), and the contribution of volcanic debris is small or absent. Besides the Cowlitz Formation, the published literature suggests that reservoir-quality sandstones may also occur in the Eocene Yamhill, Coaledo, McIntosh, Spencer, Eugene, and Skookumchuck Formations; the Eocene Puget Group; the Eocene and Oligocene Lincoln Creek and Makah Formations; the Oligocene Yaquina Formation; the Miocene Astoria Formation; and the Miocene and Pliocene Montesano and Quinault Formations (figs. 3, 4; Anderson, 1959; Armentrout and Suek, 1985; Bergen and Bird, 1972; Braislin and others, 1971; Niem,1988; Niem and Niem, 1985; Niem and others, 1990; Palmer and Lingley, 1989a, b; Snavely, 1987; Snavely and others, 1980; Walsh and Lingley, 1990; Washington Division of Geology and Earth Resources Staff, 1988). Sandstones in the Eocene Skookumchuck Formation, a temporal equivalent of the Cowlitz Formation, are excellent reservoir rocks in the Jackson Prairie gas storage project in southwestern Washington (McFarland, 1983; Wurden and Ford, 1976).

PLAY IDENTIFICATION

After considerable discussion, the assessment committee (see Mast and others, 1989) decided that only one play, the Tertiary gas play, is significant for individual assessment of undiscovered conventional petroleum resources in onshore western Oregon and Washington. The assessment of the Tertiary gas play rests on the following major assumptions: (1) the main hydrocarbon resource in the area is gas; (2) no oil accumulations as large or larger than 1 million barrels of are likely to be found; and (3) Mist gas field, the only producing field in the area, is an analog for future commercial discoveries of gas.

The committee reviewed and discussed, but did not assess, some highly speculative and nonconventional plays. For example, Snavely and Wagner (1982) speculated in an offshore-onshore geologic cross-section that Oligocene and Miocene rocks similar to the Hoh melange and broken formation may underplate strata as old as the lower Eocene Crescent Formation in Washington. Hydrocarbons generated in the underthrust melange could be trapped in fractured melange reservoirs in anticlinal structures beneath a thrust sheet of volcanic rock, or migrate upward along fractures into the overlying sedimentary rocks. The committee discussed these ideas at length but decided that there was not enough geologic information available to assess them. Future deep drilling and geophysics (including gravity, magnetotelluric surveys, and seismic reflection and refraction) may provide enough information to evaluate the underplate model at some later date.

The committee also considered the possibility that oil and gas might be found in fractured reservoirs in the Ozette and Hoh melange and broken formation along the Washington coast. This possibility was rejected, however, because the committee felt that the general lack of good reservoir rocks precluded the likelihood of finding accumulations larger than 1 million barrels of oil or 6 billion cubic feet of gas.

Finally, the committee did not attempt to assess coal bed methane, which is considered to be a non-conventional resource. Such resources may be considerable in western Washington, where estimates range from a minimum of 0.3-3.0 trillion cubic feet to a maximum of 2.6-24 trillion cubic feet (Choate and others, 1984). Nor did the committee assess "tight gas reservoirs" (Law and Spencer, 1988), although the requisite conditions for such reservoirs--including sandstones and shales with low porosity and permeability, and gas-prone source rocks--are present within Province 72.

TERTIARY GAS PLAY

General description

The Tertiary gas play includes Tertiary strata in all of western Oregon and Washington (Province 72); the area of the play is the same as the province, about 96,900 km^2 (37,400 mi^2). The play is based on the assumption that the

Mist gas field is an analog for all undiscovered hydrocarbon accumulations larger than 1 million barrels of oil or 6 billion cubic feet of gas.

Reservoirs

Based on the experience at Mist, the best potential reservoirs are quartzofeldspathic sandstones derived from a continental provenance and deposited during periods of reduced volcanic activity in high-energy depositional environments such as fluvial channels and wave-dominated, shallow-marine shelves (Armentrout and Suek, 1985). Such sandstones are known to occur in several units, for example the Eocene Cowlitz and Skookumchuck Formations. High-quality reservoirs are less likely to be found in sandstones rich in volcanic-lithic fragments. Drilling experience along the western Olympic coast suggests that fractured reservoirs in the Ozette and Hoh melange and broken formation are unlikely to be commercial because they are small and have generally low permeability.

Traps and seals

Numerous folds and faults are evident on published surface geologic maps and cross sections throughout the province (e.g., Alger, 1985; Bruer and others, 1984; Johnson and others, 1984; Niem and Niem, 1984, 1985, 1990; Niem and others, 1990; Snavely, 1987; Snavely and Wagner, 1982; Snavely and others, 1977, 1980), indicating that potential structural traps are abundant. However, the consensus among explorationists is that most of the area is so structurally complex and "chopped up" that hydrocarbon accumulations will be relatively small, like those at Mist (Williams, 1984). Dipmeter interpretations suggest that few wildcats in Washington have drilled *bona fide* traps, and few seismic lines have sufficient coherency to define domes or faulted anticlines (W.S. Lingley, Jr., Washington State Division of Geology and Earth Resources, written communication, November 26, 1990).

Reportedly, some large anticlines are present in the southern Oregon Coast Range, and are as much as 32 km (20 mi) long and 10 km (6 mi) wide, with up to 910 m (3,000 ft) of vertical relief (Deacon, 1962). However, these anticlines are mainly in the Eocene Tyee and Umpqua Formations, and several exploratory wells on these structures apparently had neither significant hydrocarbon shows nor reservoir sandstones with good porosity and permeability (Deacon, 1962).

Stratigraphic traps should be common in fluvial, deltaic, and deep-sea fan deposits, where facies changes are relatively rapid and sandstone reservoirs are in many cases surrounded by shales that could act as sealing beds and perhaps also as source rocks. Other stratigraphic traps may be associated with onlaps onto basaltic basement highs (Ise, 1985), with local unconformities, and with regional unconformities like those within the upper Eocene and at the base of the upper Miocene (Armentrout and Suek, 1985). Speculatively, accumulations of petroleum may occur in stratigraphic traps in the Puget Lowland and along the east side of the Willamette Valley, where Tertiary nonmarine facies on the east interfinger with marine facies on the west (Deacon, 1962; McFarland, 1983; Petroleum Information, 1985). This nonmarine-marine transition is little explored, perhaps because much of it is buried beneath thick piles of late Cenozoic volcanic rocks erupted from the nearby Cascades (DeJong, 1987).

Potential sealing beds include shales, coals, volcanic rocks, and igneous sills (Armentrout and Suek, 1985; Snavely, 1987). The seals at Mist gas field are impermeable tuffaceous shales; such shales occur in the Cowlitz, Keasy, Smuggler Cove, Lincoln, and Blakeley Formations (Armentrout and Suek, 1985; Niem, 1988).

Source rocks, geochemistry, timing, and migration

Organic geochemical studies discussed earlier in this report show that most petroleum source rocks in the Tertiary play are organically lean and gas-prone. Shows of gas are abundant and one commercial gas field has been found, but shows of oil are few and generally small. On the basis of these considerations, the assessment committee determined that the Tertiary gas play is prospective for non-associated gas but not for oil.

Organic geochemical studies discussed earlier in this report also show that most potential source rocks in the Tertiary gas play are thermally immature with respect to the oil and gas generative zones. However, Lopatin calculations suggest that hydrocarbon generation may have occurred in depocenters where source rocks have been buried to depths of 10,000 ft or more (Armentrout and Suek, 1985). Additional quantities of hydrocarbons may have been generated in areas of unusually high heat flow, such as near igneous intrusions or along faults (Armentrout and Suek, 1985; Snavely and Kvenvolden, 1989).

In the Mist area, Lopatin calculations show that hydrocarbon generation and migration from nearby depocenters could have begun during the Oligocene, after the reservoir rocks had been sealed by upper Eocene shales and after initial trap formation (Armentrout and Suek, 1985). Maturation may have begun earlier in older source rocks in the area, if such rocks actually exist, and may be continuing today (Armentrout and Suek, 1985).

Depth of occurrence

Commercial production at Mist has been obtained from depths of 400 to 820 m (1300 to 2700 ft). Subcommercial production has been obtained in the Ocean City area at 1204-1206 m (3,952-3,958 ft), and the Willamette Valley at

916-922 m (3,004-3,027 ft). Surface hydrocarbon seeps have been reported from throughout the play (Randall, 1984).

Exploration status

More than 500 wells have been drilled in this play, with numerous hydrocarbon shows but only one commercial discovery. Nevertheless, the play is still considered a "frontier" because the drilling density is low, few deep tests have been attempted, and the geologic framework is complex and poorly understood.

SUMMARY

Much of onshore western Oregon and Washington is the site of a forearc sedimentary basin of Tertiary age. The basin is composed of sedimentary and volcanic rocks, locally as much as 7,600 m (25,000 ft) thick, that overlie Paleocene to lower Eocene oceanic basaltic crust. These rocks record a complex and largely unresolved history of clastic sedimentation punctuated by volcanism and episodes of deformation related to interactions between the North American plate and various oceanic plates. More than 500 exploratory wells have been drilled in this area since 1900, but only one commercial gas field of modest size has been found. While some shows of oil have been reported, petroleum source-rock studies indicate that the area is prospective mainly for non-associated gas. If the Mist gas field is an analog for future discoveries, most gas accumulations will be found in quartzofeldspathic sandstone reservoirs that lie updip from depocenters containing greater than 3,050 m (10,000 ft) of post-middle Eocene strata.

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FIGURE CAPTIONS

Figure 1. Map showing boundaries of Province 72 and the Tertiary gas play, and locations of geographic features discussed in text.

Figure 2. Generalized isopach map of Tertiary sedimentary rocks; area shown is the same as Figure 1 (Snavely and Wagner, 1980).

Figure 3. Correlation chart of Tertiary stratigraphic units in western Oregon and Washington (Snavely, 1987). Because this illustration is the reduction of a published figure, some type is illegible; it is not needed to convey the information intended by this illustration.

Figure 4. Supplemental correlation chart of Tertiary stratigraphic units in western Oregon and Washington (Ise, 1985). This chart shows several units mentioned in the text but not shown in Figure 3.

Figure 5. Map of the Mist gas field, showing outline of field as of December, 1984; locations of cross-sections in Figures 6 and 7; towns; and highways (with circled numbers). Redrawn from Alger (1985).

Figure 6. Cross-section A-A' of the Mist gas field (Alger, 1985). See Figure 5 for location of cross-section. The Cowlitz Formation is bounded by unconformities, and consists in this figure of two informally-named units, the Cowlitz shale and the Clark and Wilson sandstone.

Figure 7. Cross-section B-B′ of the Mist gas field (Alger, 1985). See Figure 5 for location of cross-section. The Cowlitz Formation is bounded by unconformities, and consists in this figure of four informally-named units: Cowlitz shale, upper Cowlitz sandstone, Crown sandstone, and Clark and Wilson sandstone.

Figure 8. Time-temperature reconstruction (Lopatin plot) for a depocenter in the northern Willamette Valley near the Mist gas field (Armentrout and Suek, 1985). Each oblique line represents the burial history for sediments of a given age. Vertical patterned area represents the calculated hydrocarbon generation window. Possible source rocks in the Cowlitz Formation are shown by the horizontal pattern. Area of overlapping patterns represents potential source rocks within generation window. Rocks of the lower Cowlitz Formation entered the generation window about 33 Ma; rocks of the upper Cowlitz entered the window about 3 Ma.

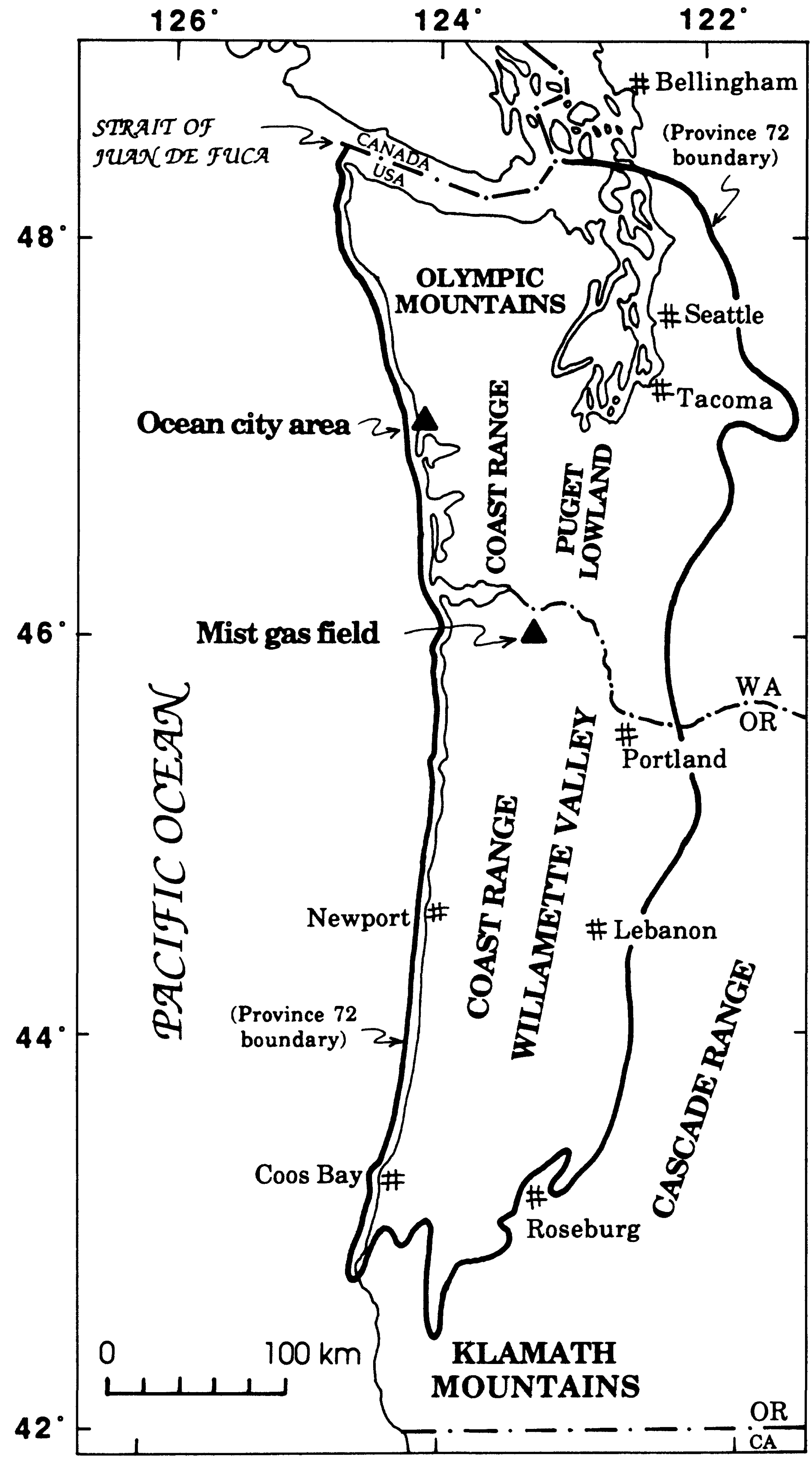
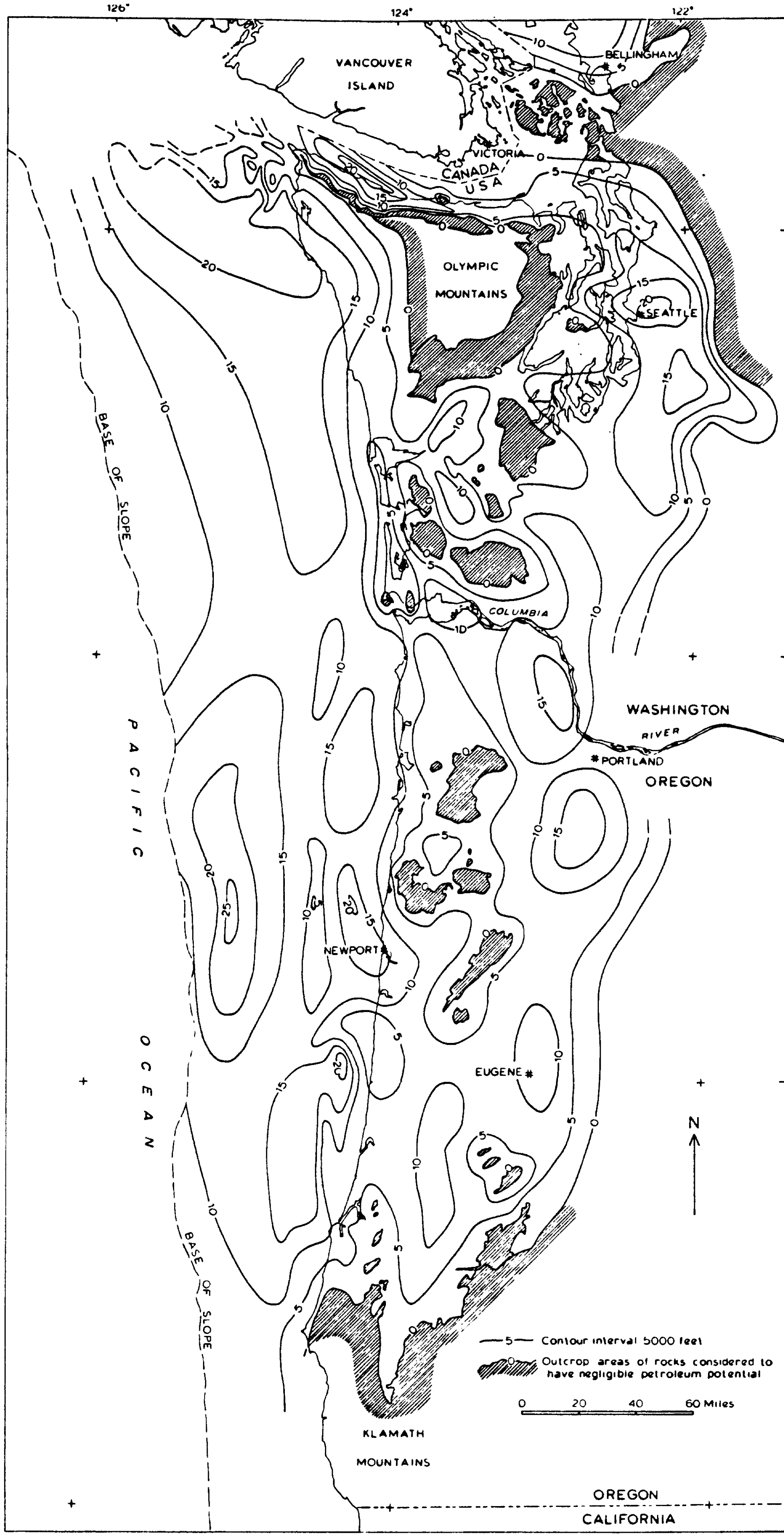
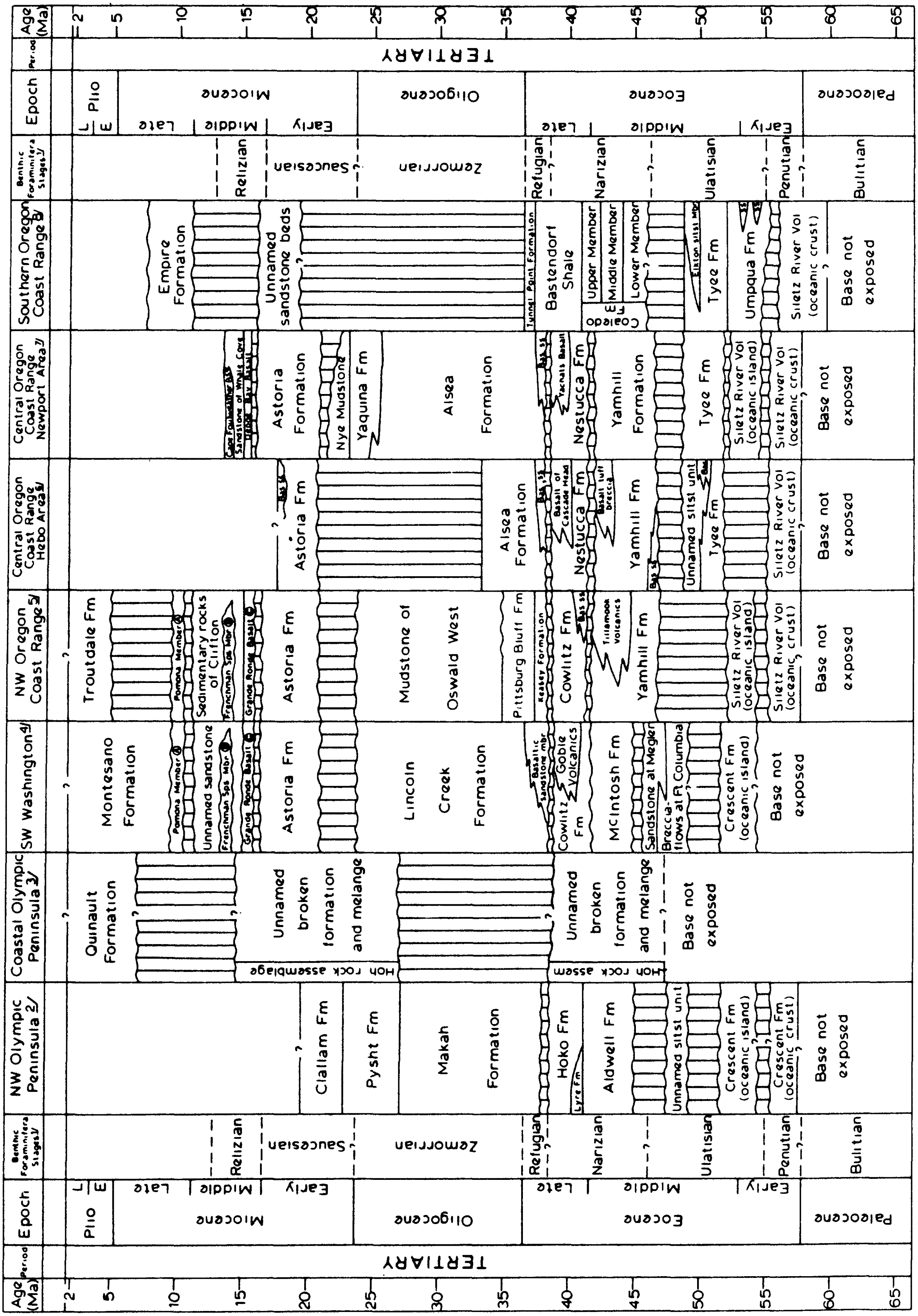

126°
124°
122°
48°
46°
44°
42°
Bellingham
STRAIT OF JUAN DE FUCA
CANADA
USA
(Province 72 boundary)
OLYMPIC MOUNTAINS
Seattle
Tacoma
Ocean city area
COAST RANGE
PUGET LOWLAND
Mist gas field
WA
OR
Portland
PACIFIC OCEAN
WILLAMETTE VALLEY
COAST RANGE
Newport
Lebanon
(Province 72 boundary)
CASCADE RANGE
Coos Bay
Roseburg
0
100 km
KLAMATH MOUNTAINS
OR
CA

Figure 1



VANCOUVER ISLAND
VICTORIA
CANADA
USA
BELLINGHAM
OLYMPIC MOUNTAINS
SEATTLE
BASE OF SLOPE
PACIFIC OCEAN
COLUMBIA RIVER
WASHINGTON
OREGON
PORTLAND
NEWPORT
EUGENE
KLAMATH MOUNTAINS
CALIFORNIA
N
Contour interval 5000 feet
Outcrop areas of rocks considered to have negligible petroleum potential
0 20 40 60 Miles

Figure 2



Age (Ma)
Period
Epoch
Benthic Foraminifera Stages 1/
Southern Oregon Coast Range 8/
Central Oregon Coast Range Newport Area 7/
Central Oregon Coast Range Hebo Area 6/
NW Oregon Coast Range 5/
SW Washington 4/
Coastal Olympic Peninsula 3/
NW Olympic Peninsula 2/
TERTIARY
Plio
Miocene
Oligocene
Eocene
Paleocene
Early
Middle
Late
Relizian
Saucesian
Zemorrian
Refugian
Narizian
Ulatisian
Penutian
Bulitian
Empire Formation
Unnamed sandstone beds
Tunnel Point Formation
Bastendorf Shale
Coaledo Fm
Upper Member
Middle Member
Lower Member
Elkton siltst Mbr
Tyee Fm
Umpqua Fm
Siletz River Vol (oceanic crust)
Base not exposed
Astoria Formation
Nye Mudstone
Yaquina Fm
Alsea Formation
Nestucca Fm
Yamhill Formation
Siletz River Vol (oceanic island)
Astoria Fm
Basalt of Cascade Head
Yamhill Fm
Unnamed sltst unit
Troutdale Fm
Pomona Member
Sedimentary rocks of Clifton
Frenchman Sps Mbr
Grande Ronde Basalt
Mudstone of Oswald West
Pittsburg Bluff Fm
Keasey Formation
Cowlitz Fm
Tillamook volcanics
Montesano Formation
Unnamed sandstone
Lincoln Creek Formation
Basaltic sandstone mbr
Goble Volcanics
McIntosh Fm
Sandstone at Megler
Breccia-flows at Ft. Columbia
Crescent Fm (oceanic island)
Quinault Formation
Unnamed broken formation and melange
Hoh rock assemblage
Clallam Fm
Pysht Fm
Makah Formation
Hoko Fm
Lyre Fm
Aldwell Fm
Crescent Fm (oceanic crust)

Figure 3

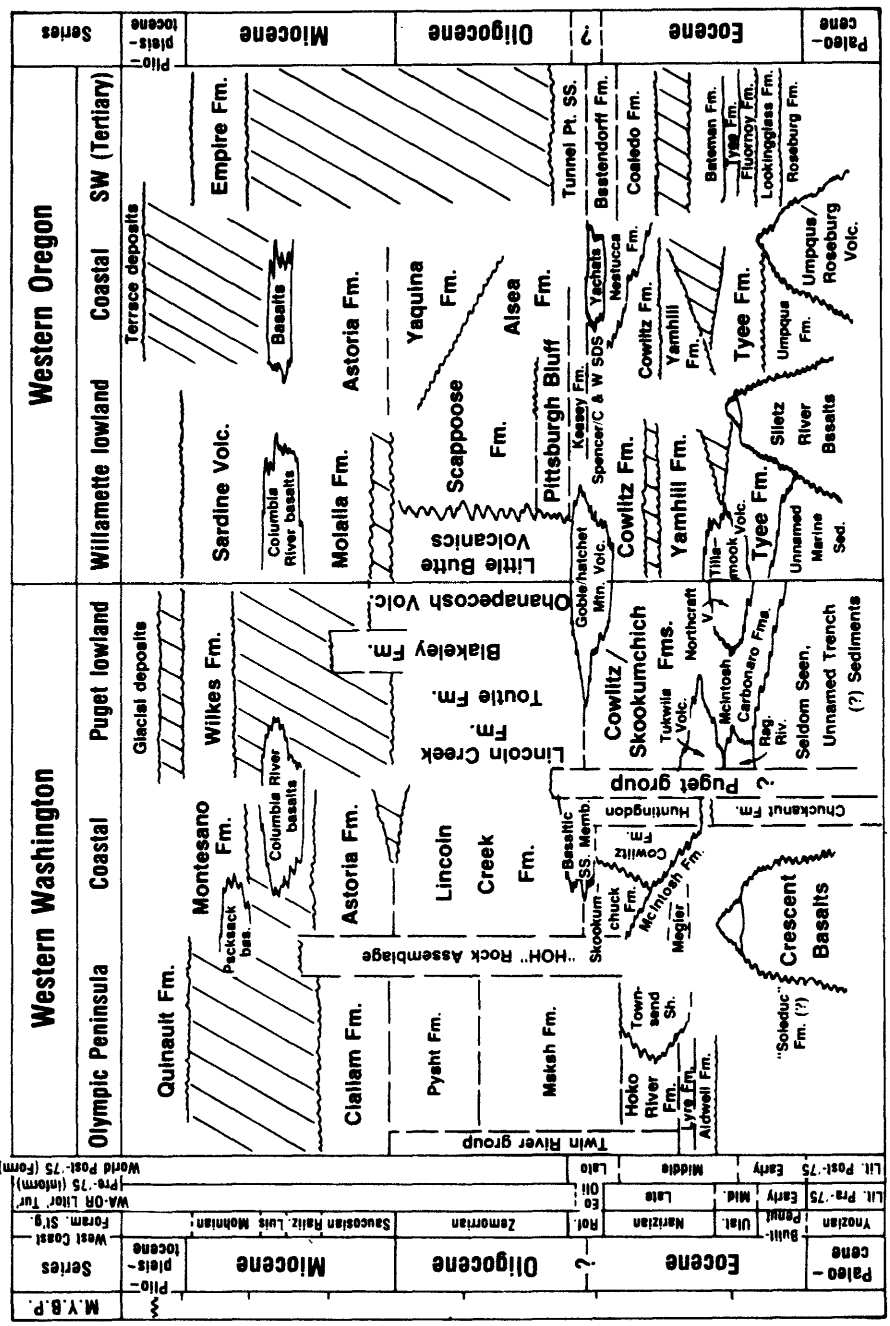
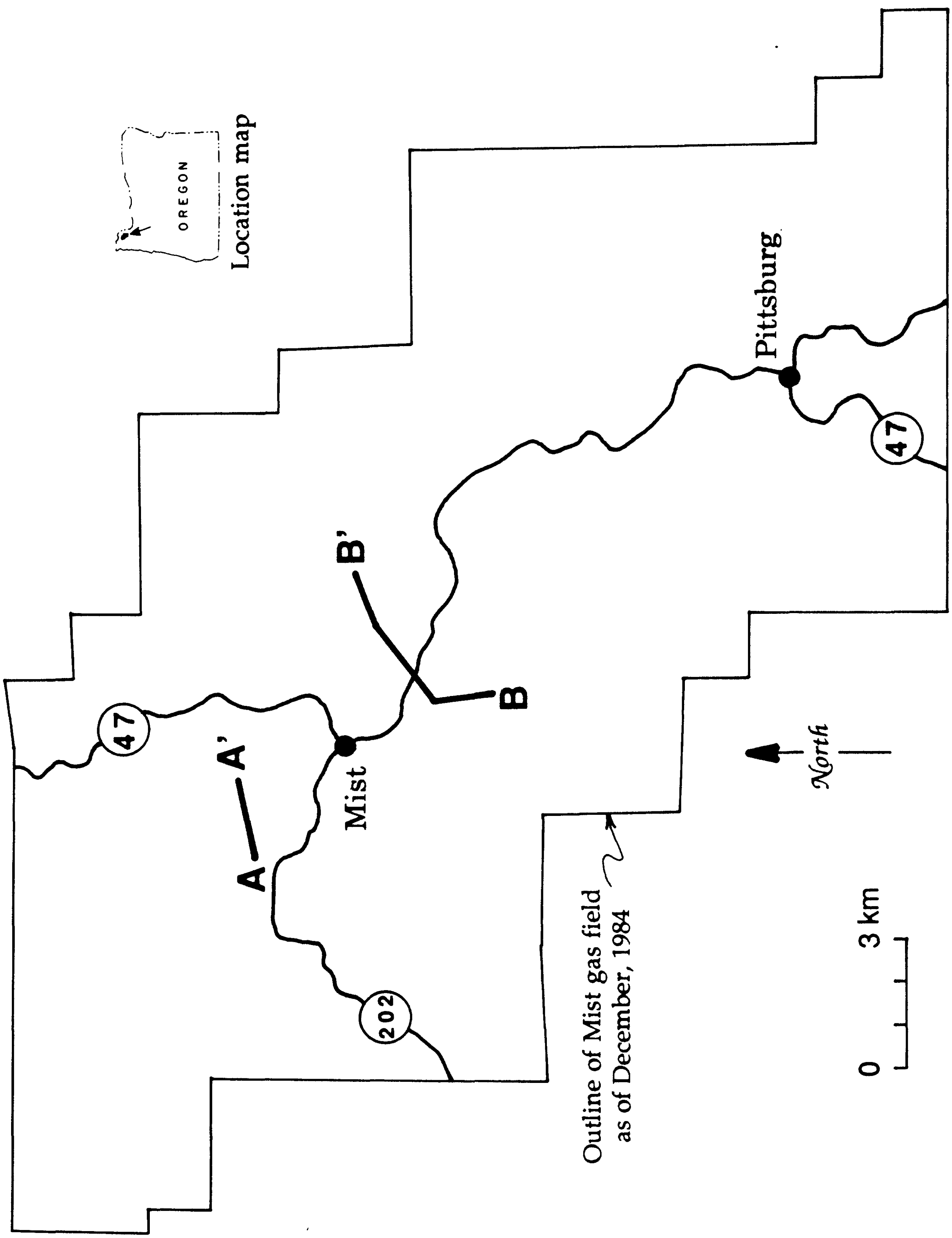

Western Washington
Western Oregon
Olympic Peninsula
Coastal
Puget lowland
Willamette lowland
Coastal
SW (Tertiary)
Series
M.Y.B.P.
Plio-pleis-tocene
Miocene
Oligocene
Eocene
Paleo-cene
Quinault Fm.
Clallam Fm.
Pysht Fm.
Makah Fm.
Twin River group
Hoko River Fm.
Lyre Fm.
Aldwell Fm.
Crescent Basalts
Montesano Fm.
Astoria Fm.
Lincoln Creek Fm.
Glacial deposits
Wilkes Fm.
Blakeley Fm.
Toutle Fm.
Ohanapecosh Volc.
Puget group
Chuckanut Fm.
Seldom Seen
Unnamed Trench (?) Sediments
Sardine Volc.
Molalla Fm.
Little Butte Volcanics
Scappoose Fm.
Pittsburgh Bluff
Cowlitz Fm.
Yamhill Fm.
Tyee Fm.
Siletz River Basalts
Terrace deposits
Basalts
Astoria Fm.
Yaquina Fm.
Alsea Fm.
Umpqua Fm.
Empire Fm.
Tunnel Pt. SS.
Bastendorff Fm.
Coaledo Fm.
Bateman Fm.
Roseburg Fm.

Figure 4



Location map
OREGON
Pittsburg
47
B'
B
47
Mist
A'
A
202
North
Outline of Mist gas field
as of December, 1984
0
3 km

Figure 5

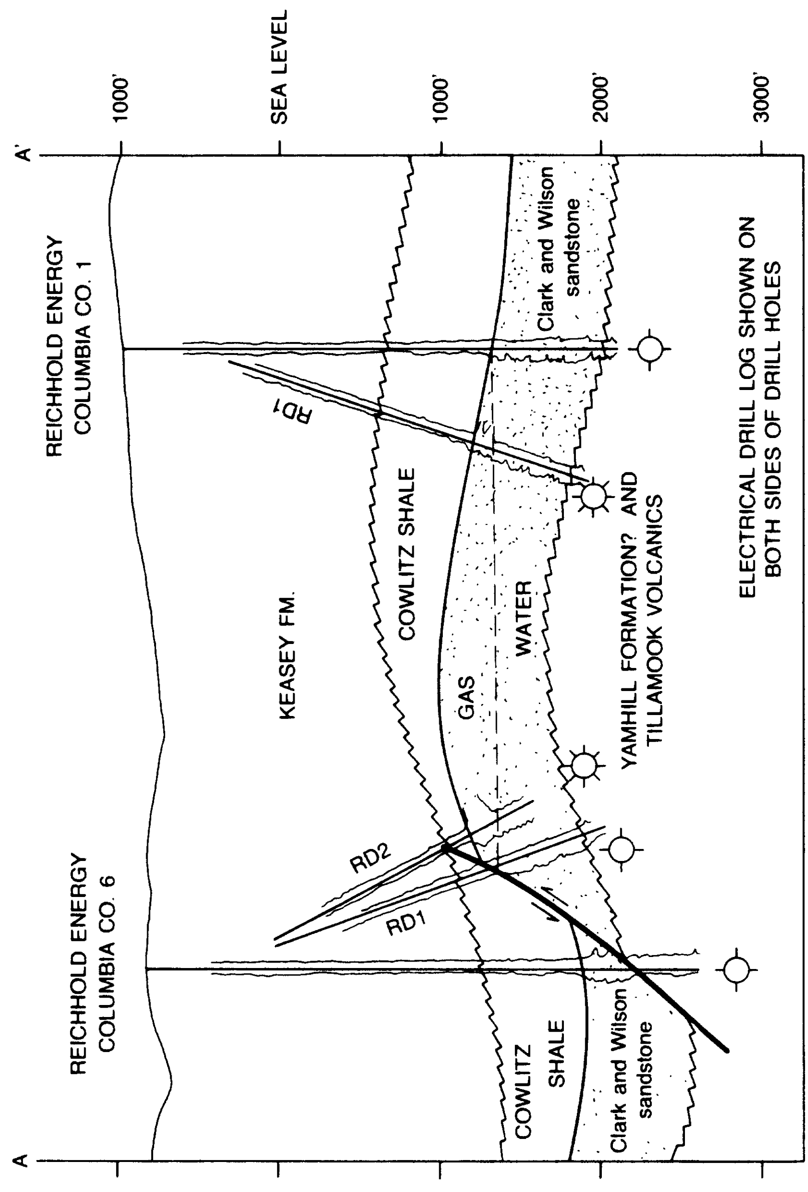

A
A'
1000'
SEA LEVEL
1000'
2000'
3000'
REICHHOLD ENERGY
COLUMBIA CO. 1
REICHHOLD ENERGY
COLUMBIA CO. 6
KEASEY FM.
COWLITZ SHALE
COWLITZ
SHALE
GAS
WATER
Clark and Wilson
sandstone
Clark and Wilson
sandstone
RD1
RD2
RD1
YAMHILL FORMATION? AND
TILLAMOOK VOLCANICS
ELECTRICAL DRILL LOG SHOWN ON
BOTH SIDES OF DRILL HOLES

Figure 6

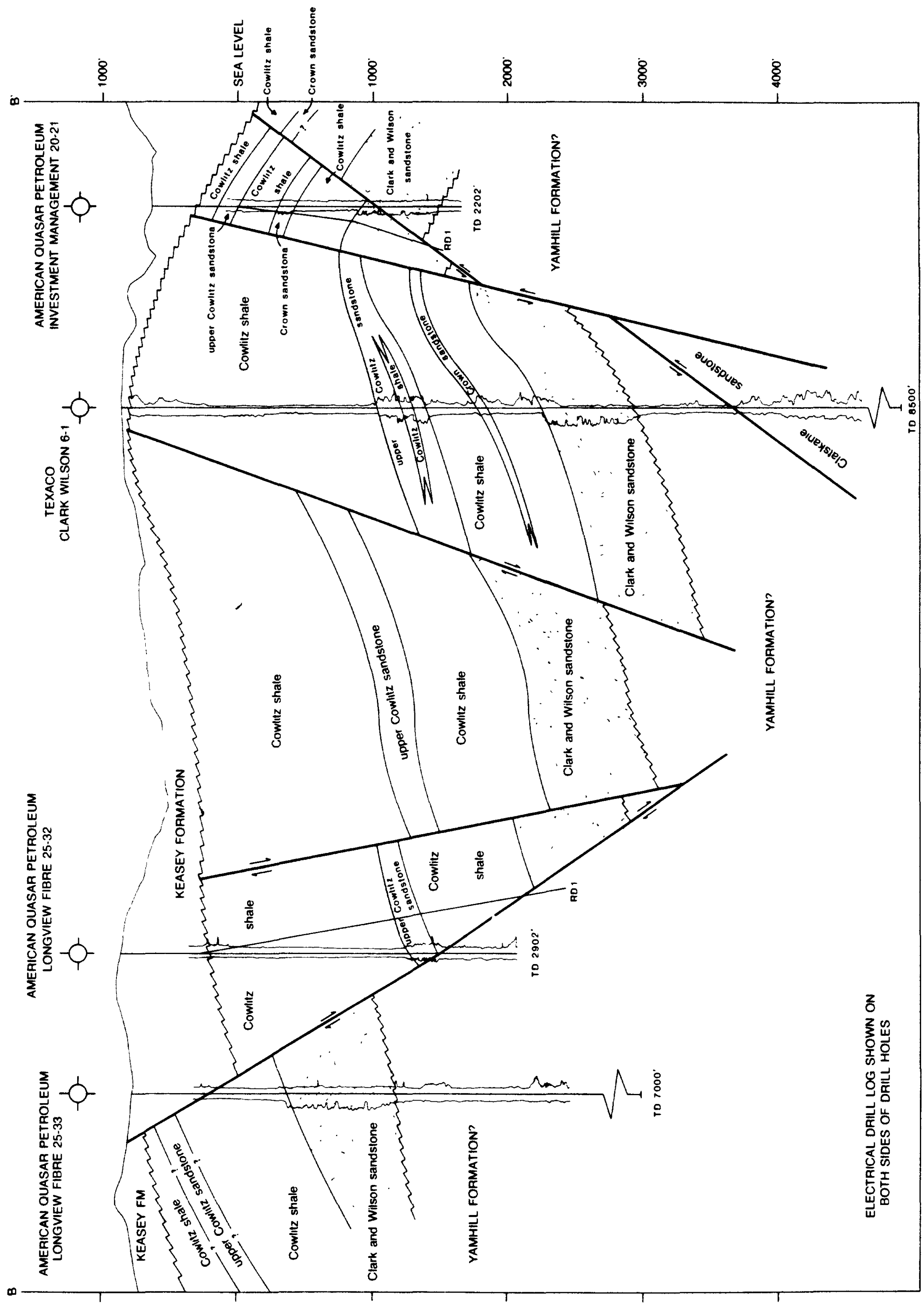

B
B'
AMERICAN QUASAR PETROLEUM
LONGVIEW FIBRE 25-33
AMERICAN QUASAR PETROLEUM
LONGVIEW FIBRE 25-32
TEXACO
CLARK WILSON 6-1
AMERICAN QUASAR PETROLEUM
INVESTMENT MANAGEMENT 20-21
SEA LEVEL
1000'
1000'
2000'
3000'
4000'
KEASEY FM
KEASEY FORMATION
Cowlitz shale
upper Cowlitz sandstone
Cowlitz shale
Clark and Wilson sandstone
YAMHILL FORMATION?
Cowlitz
shale
upper Cowlitz sandstone
Cowlitz
shale
RD1
TD 7000'
TD 2902'
Cowlitz shale
upper Cowlitz sandstone
Cowlitz shale
Clark and Wilson sandstone
YAMHILL FORMATION?
Clark and Wilson sandstone
Cowlitz shale
upper Cowlitz
Cowlitz shale
Crown sandstone
Cowlitz sandstone
TD 8500'
Clatskanie
sandstone
upper Cowlitz sandstone
Cowlitz shale
Crown sandstone
Cowlitz shale
Crown sandstone
Clark and Wilson sandstone
RD1
TD 2202'
YAMHILL FORMATION?
ELECTRICAL DRILL LOG SHOWN ON
BOTH SIDES OF DRILL HOLES

Figure 7

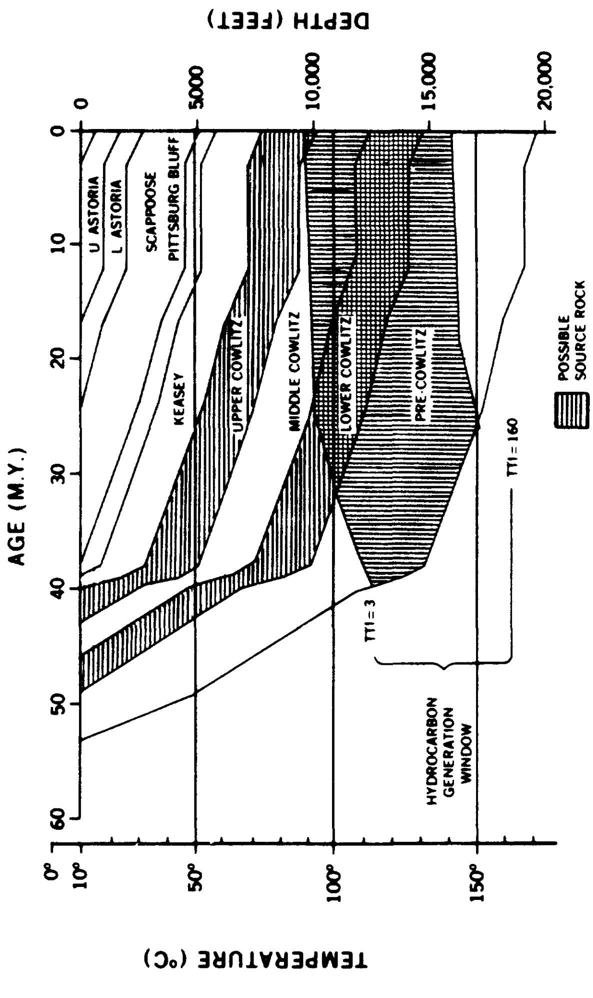

AGE (M.Y.)
DEPTH (FEET)
TEMPERATURE (°C)
0
10
20
30
40
50
60
5000
10,000
15,000
20,000
0°
10°
50°
100°
150°
U ASTORIA
L ASTORIA
SCAPPOOSE
PITTSBURG BLUFF
KEASEY
UPPER COWLITZ
MIDDLE COWLITZ
LOWER COWLITZ
PRE-COWLITZ
TTI = 3
TTI = 160
HYDROCARBON GENERATION WINDOW
POSSIBLE SOURCE ROCK

Figure 8