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Review of Geologic Framework and Hydrocarbon Potential of Eastern Oregon and Washington

By Marilyn E. Tennyson[1] and Judith Totman Parrish[1]

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[1]U.S. Geological Survey, Box 25046, MS 971, Denver Federal Center, Denver, CO

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CONTENTS

ILLUSTRATIONS

REVIEW OF GEOLOGIC FRAMEWORK AND HYDROCARBON POTENTIAL OF EASTERN OREGON AND WASHINGTON

By Marilyn E. Tennyson and Judith Totman Parrish

ABSTRACT

Petroleum resource assessment in the Pacific Northwest east of the Coast Range is complicated by extensive Cenozoic volcanic cover. Analysis of tectonic history is one approach to characterizing potentially prospective sedimentary sequences and attempting to deduce their distribution beneath volcanic rocks. Evaluation of this region for the Federal Lands Assessment Program was based on integration of regional history with lithologic and stratigraphic data from outcrops and drill holes. Two sequences with some potential are an Upper Cretaceous marine section in Oregon and an Eocene fluvial sequence in central Washington and northern Oregon.

Allochthonous terranes in the Klamath and Blue Mountains of Oregon comprise Paleozoic and Mesozoic ophiolitic, subduction complex, and arc rocks formed at southerly latitudes. Unconformably overlying Albian-Maestrichtian marine clastic rocks 4,000-8,000 ft thick (Ochoco, Mitchell, and Hornbrook sequences) demonstrate that the allochthonous terranes were in place by Albian time, then partially covered by detritus eroded from accretion-related uplifts. Eastern Washington lacks an analogous Upper Cretaceous post-accretion marine sequence.

The Eocene continental margin was characterized by oblique convergence between North America and the Kula plate. Calc-alkaline volcanism and right-lateral faulting took place east of newly accreted Coast Range basaltic basement. Crustal extension in Washington, British Columbia, and Idaho was associated with unroofing of crystalline rocks, which provided large volumes of arkosic detritus. The resulting sediments accumulated to more than 20,000 ft in strike-slip basins in central and western Washington and 0-2,000 ft in fluvial systems in Oregon, apparently outside fault-controlled basins. Cascade arc volcanism began in Oligocene time and has continued through the Neogene. In Miocene time, the Columbia River Basalt Group erupted from fissures in easternmost Washington and Oregon, flowed down west-sloping dissected topography, and lapped onto the Cascade arc. Episodic deformation accompanied volcanic activity.

In Oregon, gas, or less probably, oil, could have been generated from mature, mostly Type III organic matter in the Cretaceous sequence or from organic-rich or coaly intervals in the Eocene fluvial sequence. Eocene arkosic sandstones have adequate reservoir characteristics, but Cretaceous sandstones apparently do not. Widely scattered wells reveal marked lateral stratigraphic variation in the Cretaceous and Eocene sequences. Both are widespread, but each is locally absent and thicknesses vary.

In central Washington, drilling has shown that the Eocene fluvial sequence continues beneath Miocene basalt and that it contains some gas. Lacustrine mudstone and coal are potential source rocks present in this section where it is exposed around the perimeter of the basalt. Lopatin modeling based on published vitrinite reflectance data suggests that burial by basalt in middle Miocene time caused maturation of Eocene rocks. Porosity in samples from drill holes varies but is reported to be adequate (13-16%) in tested stratigraphic intervals.

Prospects for significant hydrocarbon accumulations in other areas within the region are considered doubtful. Upper Cretaceous rocks of the Hornbrook Formation on the eastern flank of the Klamath Mountains include mudstone and coal with marginally adequate source rock qualities for gas generation, but sandstone within the sequence has very low permeability and generally low porosity. In northwestern Washington, the quantity and maturity of organic matter in fluvial sandstone, shale and minor coal of the Eocene Chuckanut Formation is probably insufficient to have generated significant quantities of gas, although data on potential source and reservoir rock properties are unavailable. Upper Miocene, Pliocene, and Pleistocene fluvial and lacustrine strata overlying Miocene basalt in southeastern Oregon contain small amounts of gas, but it is doubtful that either source or reservoir rocks are of sufficient lateral extent that significant accumulations can be expected.

INTRODUCTION

This study has been conducted as part of the Federal Lands Assessment Program, the objective of which was to assess the potential for undiscovered hydrocarbons throughout the United States. The area addressed includes those parts of Oregon and Washington east of the Cascade Range as well as the west slope of the North Cascades in northwestern Washington, the eastern flank of the Klamath Mountains in southwestern Oregon, and the Modoc Plateau in northeastern California (fig. 1). The region is geologically complex and includes large tracts of volcanic and metamorphic rocks. The dominant geologic feature is the Columbia Plateau, a large area underlain by 10,000-12,000 ft of Miocene flood basalt, the Columbia River Basalt Group. The region has been relatively poorly explored for hydrocarbons, not only because of the widespread volcanic cover, but also because promising objectives are few, the geology is incompletely understood, and much of the terrain is rugged. Some parts of the province can be rejected outright as having essentially no potential for oil or gas. This includes the Klamath Mountains and Cascades of southern Oregon (Hammond, 1979; Irwin, 1981); the Methow basin and Okanogan Highlands of north central and northeastern Washington (Barksdale, 1975; Fox and others, 1977); and the Columbia River Basalt Group feeder-dike province of northeasternmost Oregon. All of these regions have experienced regional low- to high-grade metamorphism, volcanism, and/or intrusion.

Eastern Oregon and Washington cannot be divided easily into discrete sedimentary basins. Consequently, little conformity of terminology exists in the literature. Petroleum Information Corporation (1946) included the Harney basin in Oregon and the Yakima, Quincy, Bellingham, Lewiston, Pasco, and Umatilla basins in Washington. Montgomery (1985) included all these but the Lewiston basin and added the Snake River and Lakeview basins in Oregon and the Chiwaukum, Methow, and Republic grabens in Washington. American Association of Petroleum Geologists (1973) illustrated three basin provinces: Eastern Columbia Basin in Washington and Oregon and Snake River and Southern Oregon Basins in Oregon. Deacon and Benson (1971) illustrated the Snake River, Harney, and Lakeview Basins in southern Oregon, and Gay and Streitz (1971) inferred that a sedimentary basin under the Modoc Plateau in northern California extends partly into Oregon. Frezon and Finn (1983) did not illustrate any basins east of the Cascades. Although gas shows have been found in wells drilled in some of the purported basins, as many such wells occur outside them. Therefore,

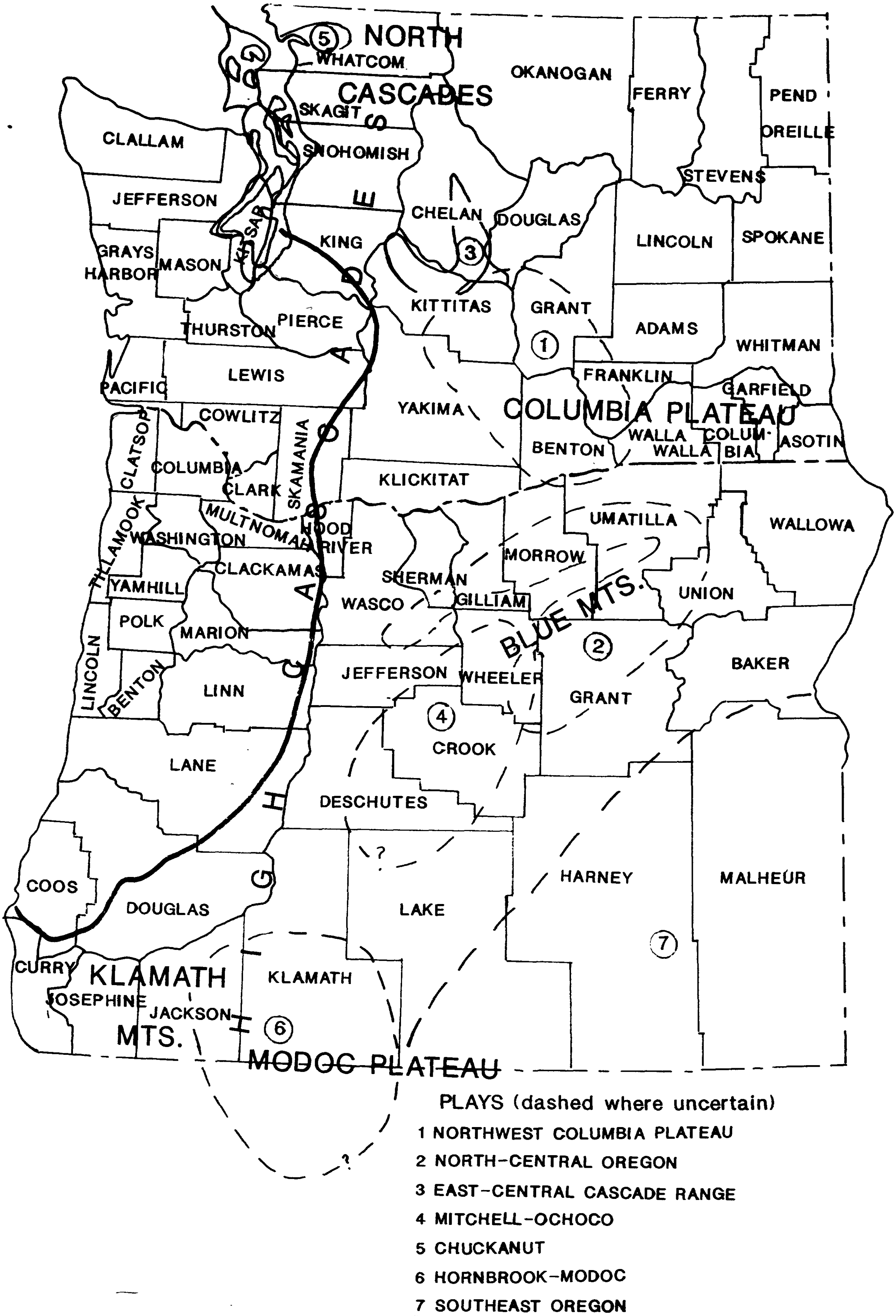

Figure 1.--Geographic index map of area discussed in report, showing counties, major physiographic features, boundary of study area, and plays described in text.

the hydrocarbon potential of eastern Oregon and Washington is not usefully described in a basin context.

Small gas fields in western Whatcom County, Washington; in the Rattlesnake Hills, Benton County, Washington; and in northern Malheur County, Oregon, are the only economic or sub-economic accumulations found to date (Newton and others, 1962; Newton and Corcoran, 1963; McFarland, 1982). None of these fields is currently active. The Rattlesnake Hills field, abandoned in 1951, yielded about 1.3 bcf of gas (Wagner, 1966); the Whatcom and Malheur County fields yielded sufficient gas for local use only.

The primary concern regarding further drilling in the province is whether hydrocarbons might be trapped under the Columbia River Basalt where recent drilling has encountered gas shows, or beneath volcanic rocks of the Oregon Cascades and Modoc Plateau. Little direct information is available concerning what lies under volcanic cover. In addition, geologic information on exposed rocks is still incomplete. Few source rock studies have been done in the province, and reservoir analysis is rare. Therefore, it is premature to reject as prospective for hydrocarbons any of the sedimentary sections which might extend beneath volcanic accumulations.

The next section is a review of the regional geologic history. It is followed by analyses of the hydrocarbon potential of the areas in this region that contain unmetamorphosed sedimentary rocks. At the end of each section is a summary of possible plays and geology relevant to hydrocarbons.

GEOLOGIC HISTORY

Rocks older than middle Cretaceous around the margins of the Columbia Plateau record a complex history of accretion of allochthonous terranes comprising subduction complexes, ophiolitic rocks, volcanic arcs and associated sedimentary rocks, all intruded by plutons of Jurassic and/or Cretaceous age. Such rocks are found around the northern, eastern, and southern margins of the basalt (fig. 2); structural trends within them delineate the "Columbia embayment" or "orocline" of uncertain origin. Paleomagnetic data suggest that pre-Tertiary rocks in the Blue and Wallowa Mountains south of the Plateau were rotated clockwise by various amounts beginning at the time of accretion and continuing in Tertiary time. Restoring these terranes to their pre-rotation positions removes much or all of the disparity in the structural trends north and south of the Plateau, although the precise timing and the mechanics of the rotations are still uncertain (Wilson and Cox, 1980; Grommé and others, 1986).

The accreted Blue Mountains island arc complex, which lies beneath the Columbia River Basalt Group in northeastern Oregon and adjacent Idaho, was emplaced against the continental margin prior to the intrusion of the mostly Upper Cretaceous Idaho Batholith (Hamilton, 1978; Hillhouse and others, 1982; Sutter and others, 1984; Lund and others, 1985; Pessagno and Blome, 1986; Vallier and Brooks, 1986; Vallier, 1986; Mann and Vallier, 1987). Emplacement must have produced high topography and a steep continental margin, with sediment shed westward into basins along the coast in central and southwestern Oregon (Hornbrook, Gable Creek/Hudspeth, Ochoco sequences, described below). This inference is based on the absence of nonmarine Upper Cretaceous sediments in easternmost Washington and Oregon and on uplift history suggested by geochronologic data from the Idaho Batholith (Sutter and others, 1984).

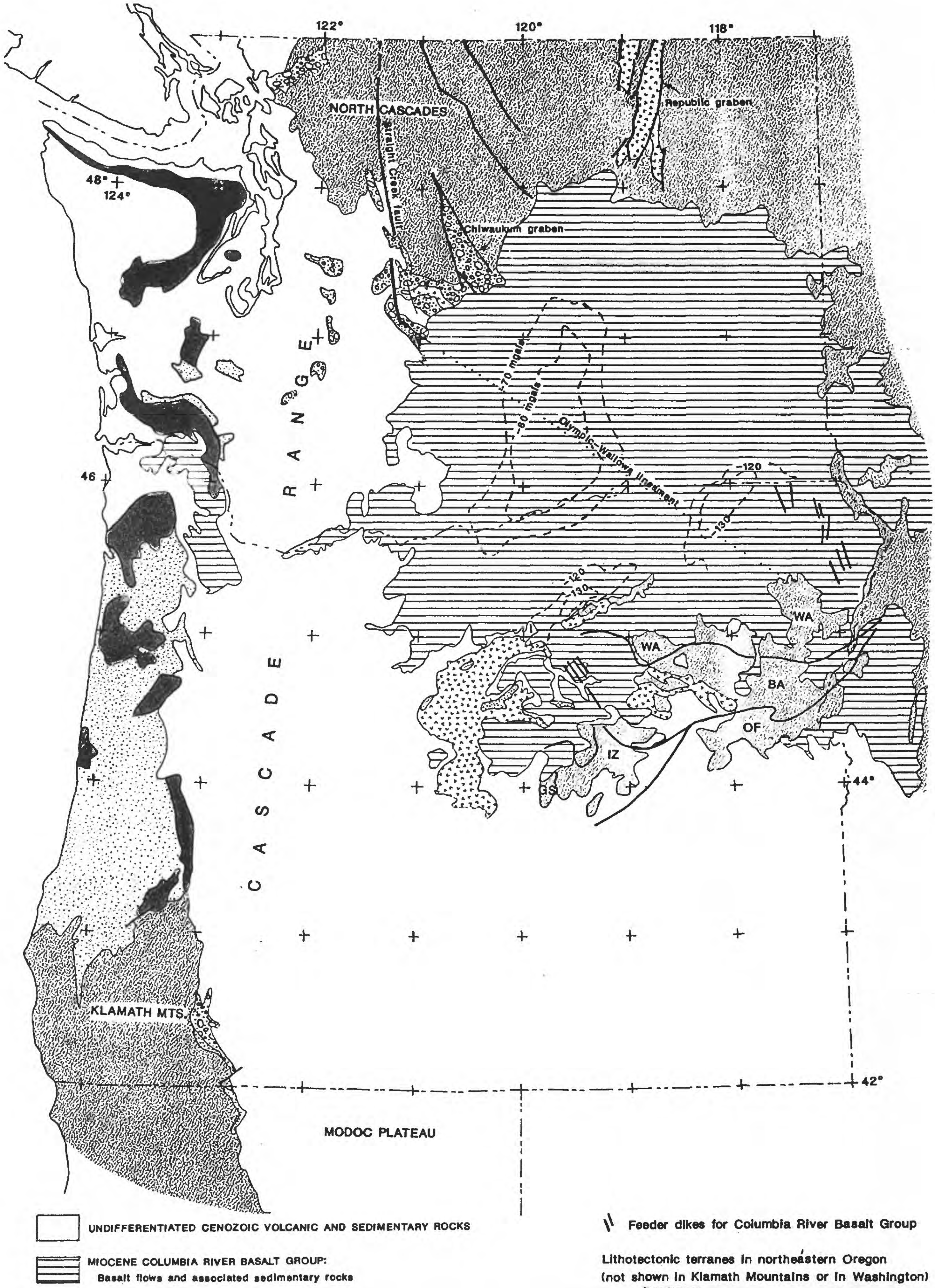

Figure 2.--Geologic index map of Washington and Oregon showing main geologic units discussed in text. Lithotectonic terranes not shown for pre-Tertiary of Washington State.

A superjacent marine clastic section unconformably overlying the western part of the arc complex in Oregon indicates arc emplacement against the continental margin by late Early Cretaceous time. This transgressive Albian and younger sequence apparently was deposited somewhat continuously along the new continental margin in Oregon because it is present in southwestern Oregon (Hornbrook Formation), in the subsurface in the "Ochoco basin" of central Oregon (Thompson and others, 1984), and in outcrops (Albian-Cenomanian Gable Creek and Hudspeth Formations) near Mitchell (fig. 3). How far northward this sequence extends beneath the Columbia River Basalt is unknown. Rocks in a tectonostratigraphically analogous position are absent at the surface in Washington. Fault-bounded Albian-Cenomanian section in the Methow basin in northern Washington was probably deposited and deformed during the middle Cretaceous emplacement of the Wrangellia superterrane against the continental margin as implied by McGroder and Mohrig (1987), who showed Wrangellia underthrusting the North Cascades in Albian-Cenomanian time. If a post-accretion sequence such as that in Oregon was ever widely deposited in northern Washington, it was subsequently eroded.

Eocene nonmarine sedimentary and volcanic rocks are extensive and locally quite thick beneath the Columbia River Basalt (fig. 3). They lie unconformably on accreted Blue Mountains arc complex rocks in eastern Oregon and locally on Upper Cretaceous marine sedimentary rocks in central Oregon. In Washington they rest mainly on metamorphic rocks accreted during Jurassic or Cretaceous time, metamorphosed and intruded during Late Cretaceous time, and uplifted on faults in Eocene time. Several factors apparently combined to cause continental sediments to begin to accumulate after widespread Late Cretaceous-Paleocene erosion. These include: (1) the resumption of local arc volcanism, which swept westward from its latest Cretaceous and Paleocene locus in the Rockies (Ewing, 1980); (2) Eocene accretion of the basaltic Coast Range basement block, apparently a cluster of seamounts of uncertain origin (Duncan, 1982; Heller and Ryberg, 1983; Wells and others, 1984; Einarsen and Engebretson, 1987), an event that modified continental margin architecture (Armentrout and Franz, 1983; Armentrout and Suek, 1985) and probably caused rearrangement of westward sediment transport patterns; (3) Eocene northwest-southeast crustal extension, detachment faulting, uplift, rotation, and unroofing of crystalline terranes in northern Washington (Harms and Price, 1983; Fox and Beck, 1985), southern British Columbia (Templeman-Kluit and Parkinson, 1986; Brown and Journeay, 1987; Carr and others, 1987), and central Idaho (Chase and others, 1983; Bennett, 1986; Wust, 1986), which, judging from uplift amounts and timing reconstructed from reset radiometric dates and fission track studies, produced a significant volume of clastic detritus (Mathews, 1981; Johnson, 1985); and (4) activity on north-trending right-lateral strike-slip faults in the North Cascades, which at least locally controlled basin subsidence and geometry (Tabor and others, 1984; Johnson, 1985; Evans, 1987). These faults were probably an onshore manifestation of right-oblique convergence between the Kula and North American plates (Johnson, 1985).

In Washington, thick sequences of Eocene fluvial and lacustrine sandstone, conglomerate, mudstone, and local coaly facies were deposited south and west of crystalline rocks in the North Cascades. These crystalline rocks were uplifted along a system of north- and northwest-trending right-lateral strike-slip faults. Stratigraphic units in this setting include the Chuckanut, Swauk, Manashtash, Chumstick, and

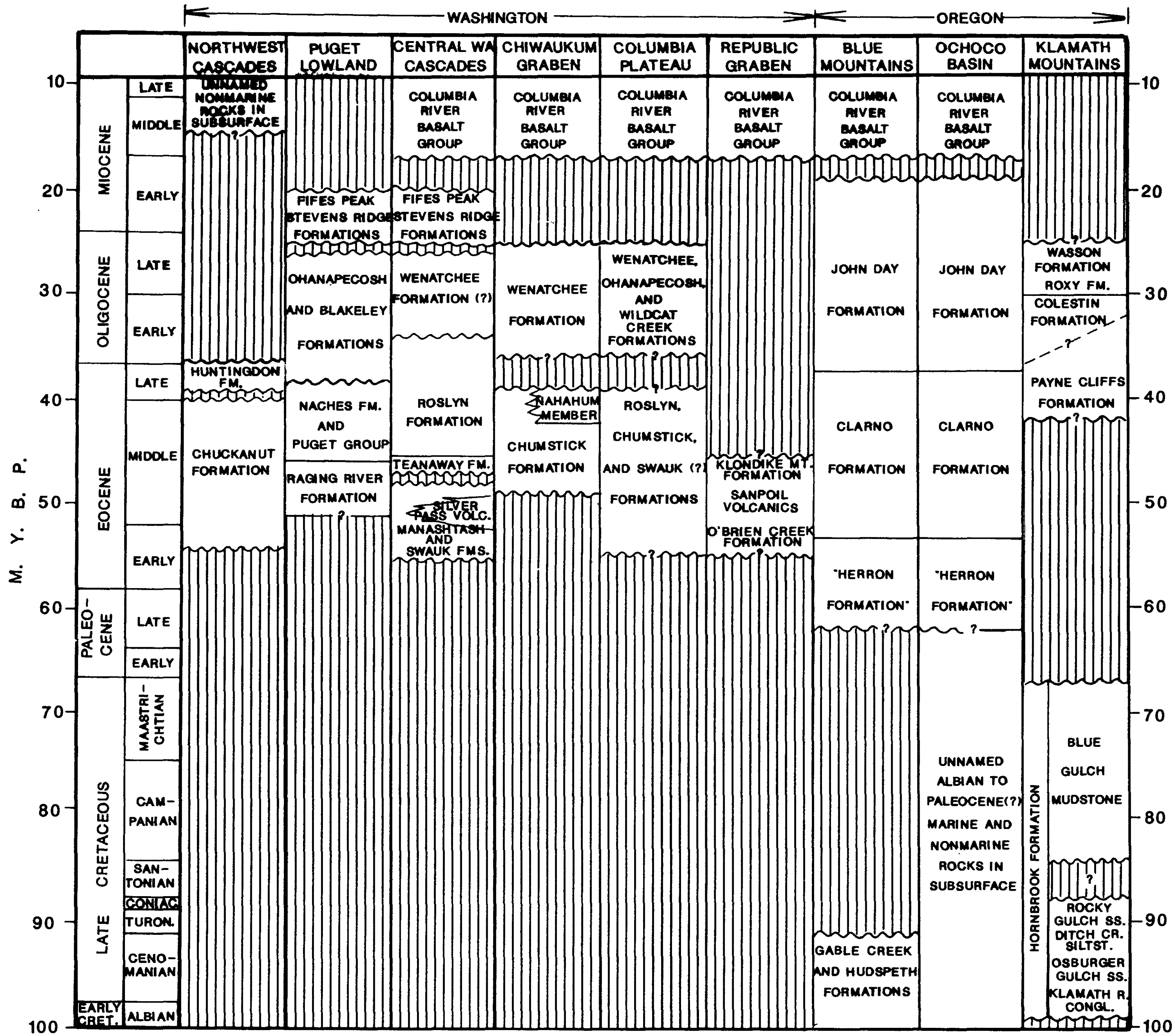

Figure 3.--Stratigraphic correlation chart for Upper Cretaceous through Miocene rocks of Klamath Mountains, eastern Washington and Oregon, and northwestern Cascades.

Roslyn Formations (Frizzell, 1979; Gresens and others, 1981; Tabor and others, 1982, 1984; Johnson, 1984, 1985). They vary markedly in thickness, from about 2,400 ft to more than 20,000 ft. In the central Cascades, tuff beds and volcanic flows are locally interbedded with these sedimentary rocks; the proportion of volcanic rocks to sedimentary rocks generally increases westward. Eocene nonmarine strata continue eastward beneath the Columbia River Basalt at least as far as the projected trace of the Entiat Fault southeast of the eastern boundary of the Chiwaukum graben (fig. 3). Toward the west across the Cascades, coeval rocks include the marine Raging River Formation and overlying westward-prograding fluvial-deltaic Puget Group, and the fluvial Chuckanut Formation in the Puget Lowland.

Early Tertiary fluvial sedimentary rocks are also widespread, although discontinuous, in north-central Oregon. They consist of a few hundred to about 2,000 ft of Paleocene or Eocene arkosic sandstone, coal, and shale (Shorey, 1976; Fritts and Fisk, 1985a,b; Ferns and Brooks, 1986; Fisk and Fritts, 1987). Unlike the Eocene sedimentary rocks in Washington, these rocks show no evidence of fault control on depositional patterns. Their source area apparently included the Idaho batholith (Heller and others, 1985, 1987), although Mesozoic accreted terranes and associated Jurassic and Cretaceous plutons also contributed detritus (Pigg, 1964; Shorey, 1976; Ferns and Brooks, 1986). Apparently, most of the sediment eroded from the unroofing Idaho batholith was transported across Oregon to a major depocenter in the forearc basin along the coast. There, deltaic and submarine ramp or fan deposits characterized by arkosic sandstones with Idaho batholith provenance reach 30,000 ft in thickness (Heller and Dickinson, 1985; Heller and others, 1987); only a relatively minor proportion of sediment appears to have been left in fluvial valleys farther east. The fluvial arkose and coal section in north-central Oregon is overlain by the Eocene Clarno Formation, a calc-alkaline volcanic arc sequence essentially similar to the Eocene volcanic rocks in Washington. Paleomagnetic evidence suggests that the Clarno Formation experienced some clockwise rotation following eruption, about 16° ±10° according to Gromme and others (1986), who interpreted the data to indicate that the Clarno Formation was erupted during the early stages of a Tertiary period of extension in Oregon. They suggested that extension in central Oregon, which began before Clarno eruption and ended between 38 and 15 m.y.b.p., accommodated clockwise rotation of the accreted Coast Range block about a pole in west-central Idaho. Restoration of extended and rotated crust in central Oregon and the Coast Range to a more easterly position makes the Idaho batholith provenance of Eocene sedimentary rocks in both of these areas much easier to explain (Heller and others, 1985; Gromme and others, 1986).

The Oligocene record consists of volcanic rocks erupted along and east of the same north-south trend as the modern Cascade arc. In western Oregon these include the Little Butte Volcanics and the Colestin, Roxy, and Wasson Formations of the Western Cascades Group (Hammond, 1979). The John Day Formation in central Oregon includes tuff beds composed of volcaniclastic detritus transported eastward from the Cascade trend as well as locally erupted trachyandesitic ash flows and alkali-basalt lavas (Robinson and others, 1984); Gromme and others (1986) suggested that John Day volcanism in central Oregon might have been associated with extension. In Washington, the Ohanapecosh Formation and Huckleberry Mountain volcanics (Frizzell and others, 1984) represent Oligocene arc volcanism.

Oligocene volcaniclastic strata are present on the eastern flanks of the Washington Cascades and are probably extensive beneath the Columbia River Basalt Group. The Wenatchee Formation, locally present on the northern margin of the basalt, consists of compositionally mature fluvial sandstone interbedded with organic-rich tuffaceous lacustrine shales above an unconformity spanning about 40 to 34 m.y.b.p. (Gresens, 1981; Hauptmann, 1983). Wenatchee-type sub-quartzose sands, probably in part recycled from Eocene sandstones, could be present beneath the Columbia River Basalt along Oligocene river valleys and would be ideal reservoir facies. Key questions involve the locations of 1) the transition from cleaner sands in the north and east to volcaniclastic-dominated sands to the south and west, and 2) the basalt-filled river valleys.

Cascade magmatism continued from Oligocene into early Miocene time, represented by the Stevens Ridge and Fifes Peak Formations and early Miocene batholiths in Washington, and by the Breitenbush and Heppsie Formations in Oregon (Hammond, 1979; Frizzell and others, 1984). About 17 m.y.b.p., flows of the Columbia River Basalt Group began to be erupted from a zone of north-northwest-trending feeder dikes in eastern Oregon and Washington (Hooper, 1982; Mangan and others, 1986). Flows first filled bedrock canyons near the feeder dikes and then spread out westward down the regional Miocene paleoslope (Reidel, 1983). Some of the more voluminous flows reached the Pacific within a few days (Hooper, 1982). Pre-basalt drainage patterns were disrupted, causing lakes to form and new channels to be cut, thus accounting for the many interbeds of fluvial and lacustrine sediments within the stack of flows. Basalt flows interfingered with west-derived Cascade volcaniclastics (Ellensburg Formation) on the west (Mackin, 1961; Swanson and others, 1979; Waitt, 1979). Most of the basalt was erupted between about 17 and 14 m.y.b.p., but volumetrically minor eruptions continued through Miocene time. Folding and reverse faulting on variable but predominantly east-west trends began early in the approximately 10 m.y. period of eruption and has continued through Neogene time (Barrash and others, 1983).

AREA 1, COLUMBIA PLATEAU

Description

Miocene flood basalts locally more than 11,000 ft thick mask the geology underlying the Columbia Plateau almost completely because seismic reflection surveys are incapable of penetrating such a thickness of basalt. Nevertheless, exploration interest in this area has been persistent, encouraged by hydrocarbon shows in several wildcat wells. The presence of at least small amounts of gas has been demonstrated. One small field, the Rattlesnake Hills field near Grandview in Benton County, produced gas between the 1920's and the 1940's (estimated total production 1.3 bcf) from a reservoir in basalt at depths between 700 ft and 1,200 ft; a deeper test hole to 10,655 ft had no shows, suggesting that the accumulation was local. Shell Oil Company had significant shows of gas in several deep holes drilled more recently in the northwestern Columbia Plateau, which will be discussed in greater detail below. Gas and tarry oil shows have been reported from a few wells drilled in exposed pre-Miocene rocks stratigraphically beneath the basalt in northern Oregon, which implies that factors favoring hydrocarbon accumulation may be present beneath the basalt in that region as well.

There are several ways of inferring the geology beneath the basalt. Analysis of the regional geologic history presented in the preceding section and extrapolation from the rocks which crop out around the margins of the basalt is one approach. Another is geophysical, using gravity, seismic refraction, and magnetotelluric surveys. The most direct information, of course, is stratigraphy revealed in deep drill holes, of which only a handful exist. A review of the insight gained from each of these approaches and an analysis of the implications for hydrocarbon occurrence follow.

Geophysical Data

A large positive gravity anomaly in the west-central part of the area covered by basalt (fig. 2) has been variously interpreted. It is elongate in a northeasterly direction and its southeastern margin is a steep, linear regional gradient parallel to the Blue Mountains, which Riddihough and others (1986) have speculated might be a clockwise-rotated, continent-bounding, strike-slip fault of Mesozoic age that originally trended north-south during Mesozoic accretion; Mesozoic oceanic crust would have lain to the west (now northwest) side. The anomaly itself probably is attributable at least in part to the 10,000-12,000 ft (3-4 km) thick stack of basalt flows, but many workers believe that unusually dense, presumably oceanic crust at some depth beneath the Plateau also is partly responsible for the anomaly (see discussions in Fritts and Fisk, 1985a,b, and Barrash and others, 1983).

Seismic refraction studies are not particularly helpful in resolving sub-basalt geology. A north-south unreversed refraction profile across the Columbia Plateau indicates some combination of crustal thinning and higher P-wave velocities beneath it, with a strong contrast in crustal properties between the granitic and metamorphic highlands in northeastern Washington and the crust beneath the Plateau (Hill, 1972). Catchings and others (1984) reported results from a shorter, reversed line that suggested thicknesses of about 16,000-33,000 ft (5-10 km) for the basalt, significantly greater than thicknesses observed around the margins or in drill holes. Their results also indicate that several refracting layers and fault scarps are present within the crust beneath the basalt, and that the crust is about 25 mi (40 km) thick, not 16-18 mi (25-30 km) as earthquake studies have suggested.

Magnetotelluric surveys, which involve long-range resistivity measurements, are useful in distinguishing sedimentary rocks, which are more porous and conductive, from the more resistive basalt layer and from basement. Stanley (1984) interpreted results of an east-west survey across the northern Plateau to indicate a lens of basalt up to 10,000-13,000 ft thick overlying a sedimentary layer that thickens westward from about 3,000 ft in northeastern Washington to as much as 11,500 ft beneath the western half of the Plateau (fig. 4). It maintains its maximum thickness where the survey line crosses the projection of the Chiwaukum graben, then thins and pinches out westward against a basement high near the projected trace of the Olympic-Wallowa lineament northwest of Yakima. The thicknesses of both the basalt and the underlying sedimentary rocks shown on Stanley's (1984) interpretation are reasonably consistent with the thickness revealed by recent deep exploratory wells (described below) although the sediment thickness is markedly less than the measured thicknesses of exposed Tertiary stratigraphic units in the Chiwaukum graben and Swauk basin north of the survey line where Eocene

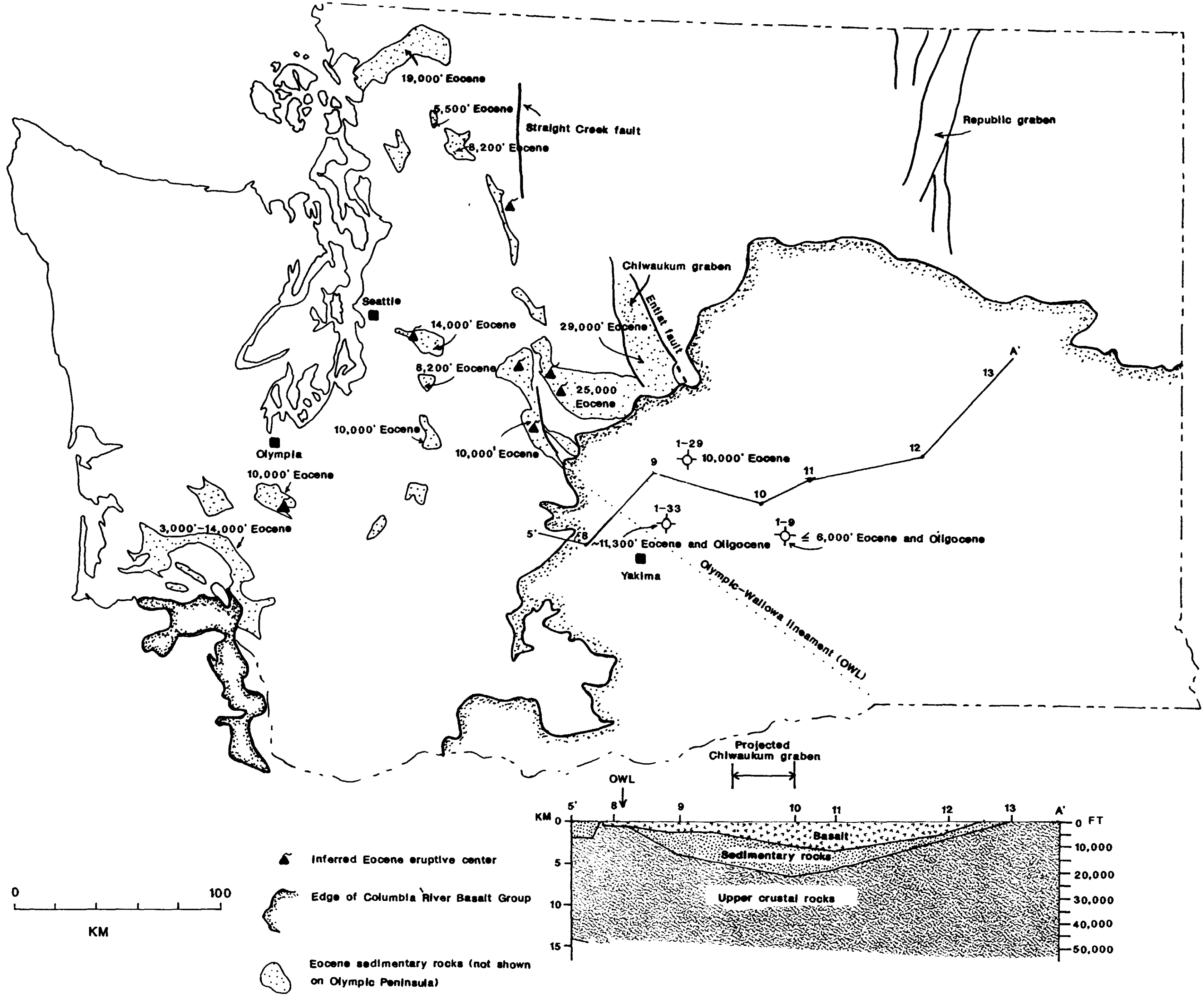

Figure 4.--Map showing survey lines of magnetotelluric study of Stanley (1984) and interpretation of eastern part of his line A-A'. Generalized thicknesses of Eocene sedimentary rocks from outcrops and subsurface data and inferred eruptive centers are also shown for reference.

section is as much as 25,000-30,000 ft thick. The inferred presence of sedimentary rocks beneath the basalt east of the project of the Chiwaukum graben is significant. These rocks are most likely to be Eocene or Oligocene on the basis of regional considerations and could consist of west- and southwest-transported fluvial sedimentary rocks, east-transported volcaniclastic rocks of general Cascade provenance, or both.

Deep Drill-Hole Data

Four holes drilled to depths greater than 10,000 ft (fig. 5) provide important glimpses of subsurface relationships in central Washington. The Standard Rattlesnake Hills-1 went to 10,655 ft in 1958. It had no shows and failed to reach the bottom of the Grand Ronde flow, a major flow near the base of the Columbia River Basalt Group (T.J. Walsh, oral commun., 1987). Three wells drilled between 1982 and 1985 by Shell penetrated sub-basalt sedimentary and volcanic rocks (fig. 6), and all encountered noncommercial gas shows. The 1-33 Yakima Minerals, TD 16,199 ft, penetrated about 5,000 ft of basalt and about 5,000 ft of Oligocene volcanic and volcaniclastic rocks overlying about 6,000 ft of Eocene sandstone, siltstone, shale, coal, and tuff assigned to the Swauk, Teanaway, and Roslyn Formations (Campbell and Banning, 1985). The 1-29 Bissa well went to 14,965 ft; the base of the basalt was encountered at about 4,500 ft. It was drilled on the Naneum Ridge, a north-south-trending structural high on strike with the Leavenworth Fault, which bounds the west side of the Chiwaukum Graben farther north. It encountered about 9,000 ft of sandstone, siltstone, shale, and coal correlated by Campbell and Banning (1985) with the Roslyn Formation in the Cle Elum area (Walker, 1980), overlying more than 1,000 ft of brown and black shale with minor thin limestone, siltstone, and sandstone. Although Campbell and Banning (1985) called these older rocks a "Cretaceous marine" sequence, they are probably equivalent to Eocene Swauk Formation (S.Y. Johnson, oral commun., 1987; T.J. Walsh, oral commun., 1987), which includes calcareous paleosols. They overlie "granite," which could be either gneiss like the Swakane gneiss east of and beneath the Chiwaukum graben; granitic fanglomerate deposits like those at Mission Ridge (Tabor and others, 1982) adjacent to the Leavenworth Fault; or possibly a pluton related to the Cretaceous Mt. Stuart granodiorite west of the Chiwaukum Graben. Comparatively little information is available from the 1-9 Burlington Northern (TD 17,518 ft), the farthest east of the three tests. The bottom of the basalt was encountered at about 11,500 ft, overlying about 1,500 ft of tuffaceous Oligocene section with porosities of up to 15-17% (W.S. Lingley and T.J. Walsh, 1986, oral commun., 1987). Below this unit about 4,500 ft of section correlated with Eocene Chumstick Formation was drilled, with porosities ranging between about 5% and 14%. Several gas shows were tested; condensate was tested at about 13,380 ft in the "Chumstick" (Lingley and Walsh, 1986). Little information is available about the lithology of the sediments which were tested. Speculation is that the gas in the well might have been commercial if drilling costs had been lower.

Several conclusions can be drawn from the stratigraphic information revealed by drilling in the northwestern Columbia Plateau.

(1) Clearly the basalt thickens southward toward the "Pasco basin" (Waitt and Swanson, 1986; Reidel and others, 1987), although the 10,665 ft of basalt drilled in the Rattlesnake Hills well does not approach the 5-10 km estimate for basalt thickness made from seismic refraction

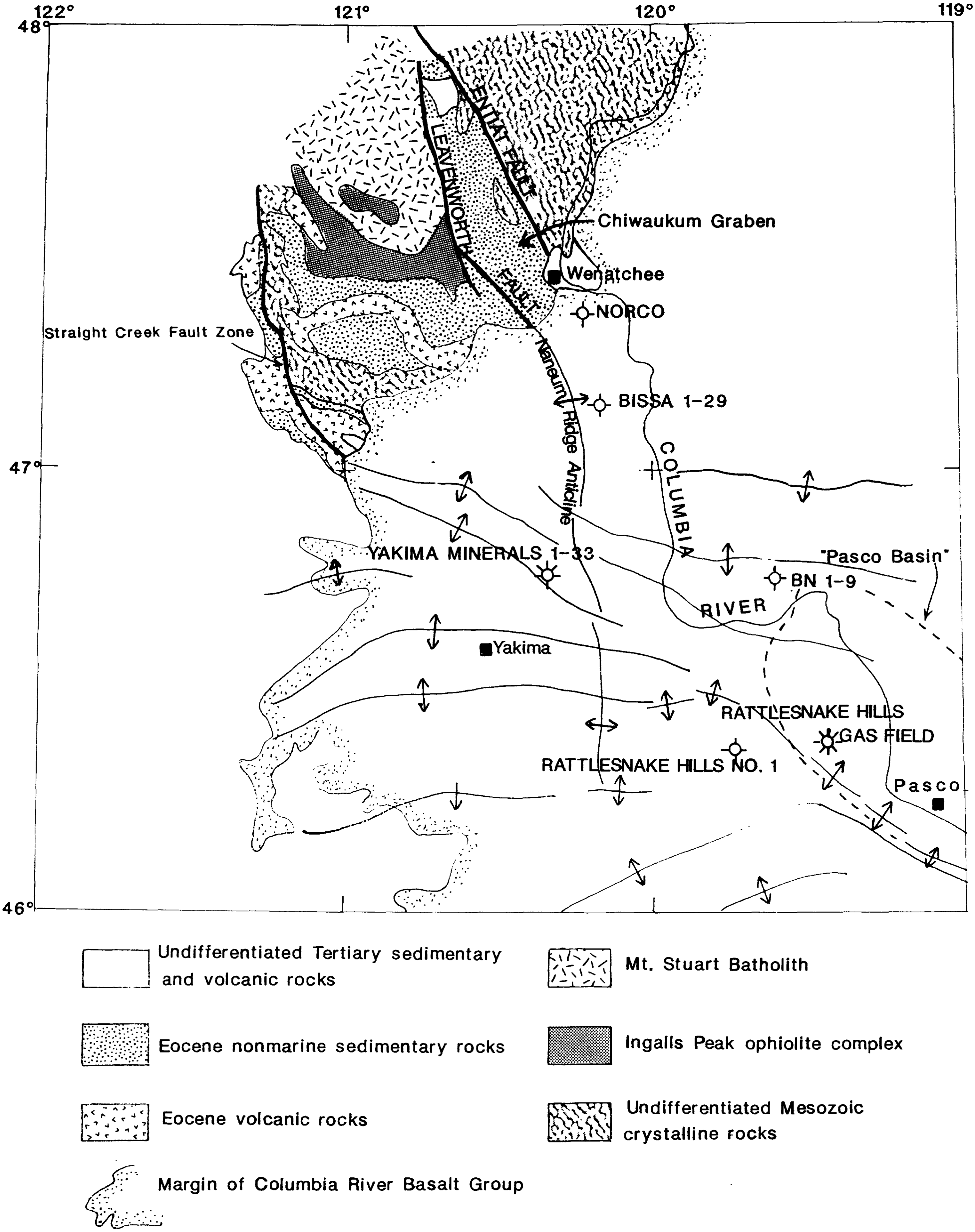

Figure 5.--Geologic sketch map of northwestern Columbia Plateau margin showing geologic features discussed and locations of wells mentioned in text.

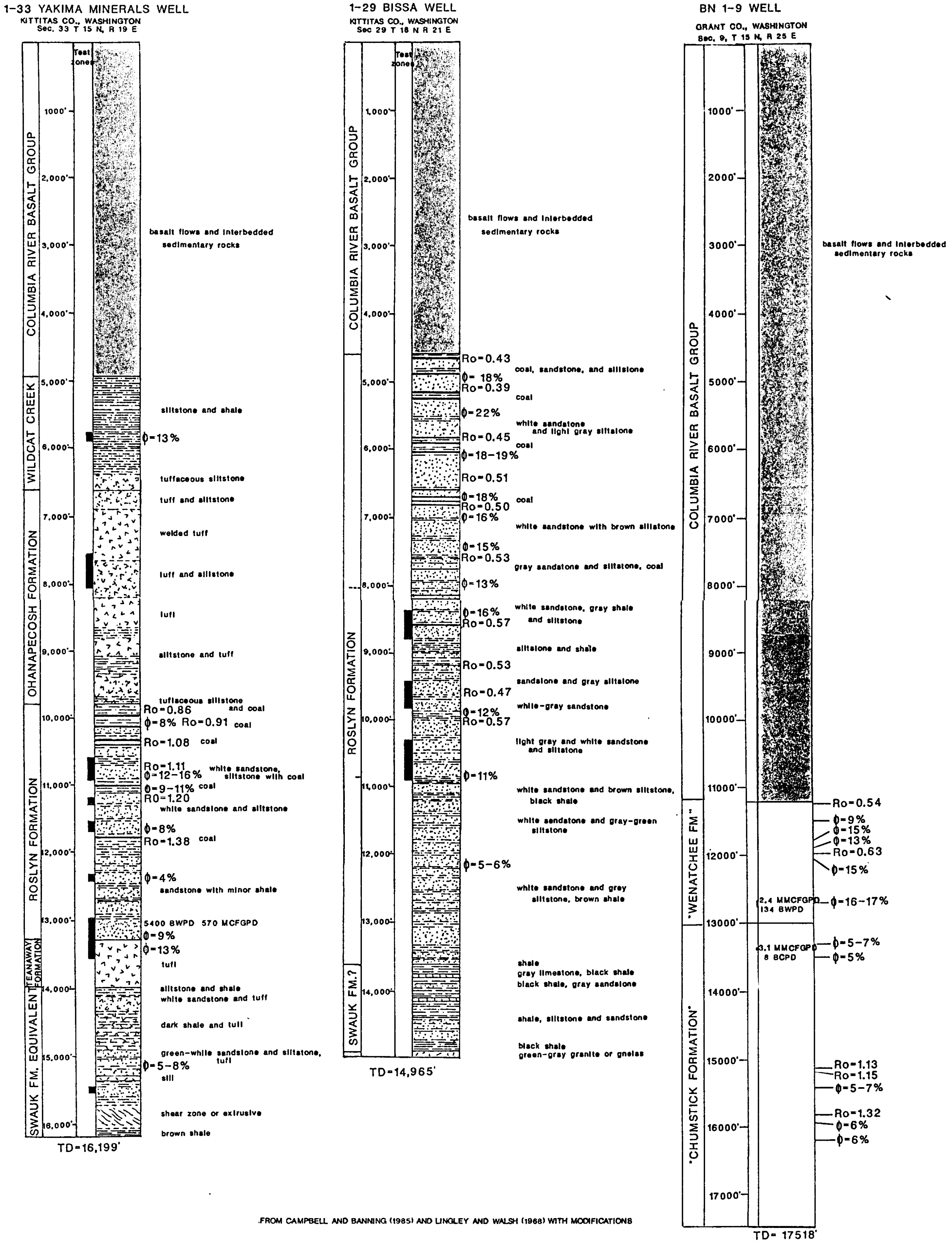

Figure 6.--Stratigraphy in three Columbia Plateau wells, from Campbell and Banning (1985) and Lingley and Walsh (1986)

results by Catchings and others (1984) in the Hanford area. The basalt would have to thicken precipitously south of the 1-33 Yakima and 1-9 BN wells to reach such a thickness.

(2) The wells failed to encounter widespread clean sands of the Oligocene Wenatchee Formation or the overlying Miocene shales composed of swelling clays that have been the objects of speculation as ideal reservoir and seal beneath the basalt (Gresens and Stewart, 1981; Curry, 1984). In the 1-33 Yakima, red, green, and lavender shales, siltstones, and tuffs of the Oligocene Wildcat Creek Formation underlie the basalt, and in the 1-29 Bissa, coal, siltstone, and sandstone of the Eocene Roslyn Formation lay immediately below the basalt. This indicates that the basalt flowed over dissected topography, including a probable paleo-structural high, rather than a flat, aggrading fluvial-lacustrine surface. Accordingly, Wenatchee-type reservoirs probably would be at best locally developed in paleovalleys beneath the basalt.

(3) Oligocene volcaniclastic rocks of Cascade provenance extend eastward some distance beneath the basalt but may have been confined to the area west of the Naneum Ridge high on which the 1-29 Bissa was drilled. More data from the 1-9 BN well are needed to corroborate this speculation.

In northern Oregon (fig. 7), subsurface data suggest that marine and nonmarine Mesozoic sedimentary rocks are present south of the Blue Mountains anticlinorium beneath the Tertiary volcanic cover, which thickens to the north. Only one well, the Standard Kirkpatrick (Fox and Reidel, 1987), penetrated the Columbia River Basalt Group; it went through 2,440 ft of basalt overlying 4,255 ft of Oligocene John Day and Eocene Clarno volcanics, which in turn overlie marine Mesozoic argillite and sandstone over 2,000 ft thick. These latter rocks have yielded pollen with Late Jurassic and Early Cretaceous ages. Most of the rest of the wells were spudded in Clarno or John Day volcanics, which evidently formed topographic highs onlapped by Miocene basalt flows (Rogers, 1966; Fisher, 1967). The thickness of Clarno Formation ranges from about 1,000 to over 6,500 ft in these wells, increasing northward, except north of the Blue Mountains in the Kirkpatrick well where it may be only a few hundred feet thick (Fox and Reidel, 1987). In two wells there is a pre-Clarno nonmarine sand-bearing sequence of latest Cretaceous or Paleogene age: according to well reports, the Northwest Morrow penetrated a sequence about 600 ft thick of mostly mudstone with possible friable sandstone beds and coal, and the Texaco Federal drilled through about 500 ft of a probable nonmarine section identified as Maestrichtian to Paleocene (Thompson and others, 1984). Albian to Campanian sediments deposited in nonmarine, neritic, and bathyal environments lie beneath the Clarno in wells near the town of Clarno (Clarno No. 1, Kleinhans and others, 1984) and in the "Ochoco basin" south of Mitchell (fig. 9). Thicknesses range between about 400 ft and 1,400 ft for the Albian and Cenomanian, which is present in most wells, and 1,400 to 2,100 ft for less laterally extensive younger Upper Cretaceous rocks. The distribution of the Cretaceous rocks suggests a basin with a northeast-trending shoreline along its southeast edge, and a possible "outer-arc high," which may have been intermittently emergent, forming its northwest margin. This high probably consisted of the older deformed Jurassic and Cretaceous trench-wall sediments (Kleinhans and others, 1984) which have been drilled in the Kirkpatrick and Ochoco basin wells.

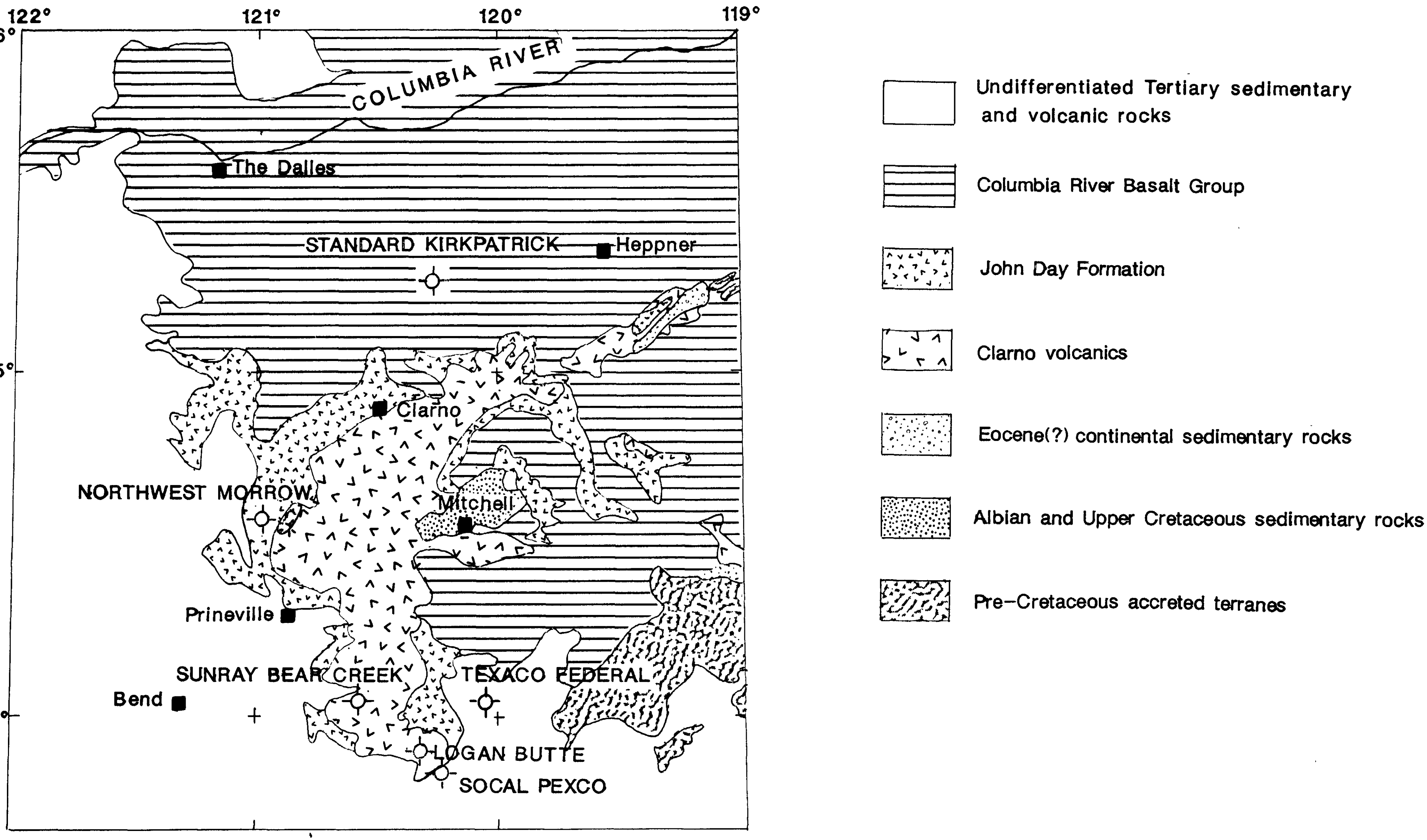

Figure 7.--Geologic sketch map of north-central Oregon showing major rock units and locations of wells mentioned in text.

Oil and gas shows are mentioned in well reports from a few of the wells in Oregon. Six shows were reported in pre-Clarno sediments in the Northwest Morrow near Grizzly, at depths of about 2,500-3,000 ft. The Burgess #2 near Clarno had gas and oil shows below 2,500 ft in pre-Clarno shales, probably Cretaceous or older. The Pexco #1, in the Ochoco basin area south of Mitchell, encountered tarry oil shows in pre-Upper Cretaceous rocks of uncertain lithology, described in well reports as tuff, claystone, and graywacke.

Possible Hydrocarbon Settings

The most promising plays beneath the Columbia River Basalt Group are within either fluvio-lacustrine rocks in Eocene strike-slip basins in central Washington or in apparently regionally-deposited Upper Cretaceous marine and Eocene-Oligocene fluvio-lacustrine sequences. These settings differ mainly in the greater presumed thickness of Eocene section and higher probability of lacustrine facies in strike-slip controlled basins, and in the slightly greater prospects for oil where marine Cretaceous section is present.

The most likely locations for grabens beneath the basalt are difficult to infer. The Chiwaukum graben could continue for some distance to the south. This possibility is supported by both 1) the presence of the Naneum Ridge structural high along strike with the Leavenworth Fault bounding the west side of the graben and 2) the zone of relatively thick (11,500 ft) sedimentary rocks suggested by the magnetotelluric study of Stanley (1984) along the projected trend of the Chiwaukum graben (fig. 4). Stanley's (1984) interpretation also shows the sub-basalt sedimentary sequence pinching out about where the Olympic-Wallowa lineament intersects the survey line. This lineament (Raisz, 1945; Tabor and others, 1984; Tabor, 1986), the tectonic significance of which has never been established, cuts southeast across the Plateau from the southernmost exposures of the Swauk-Teanaway-Roslyn sequence southwest of the Chiwaukum graben (fig. 2). The traces of the southernmost Eocene faults related to the major right-lateral Straight Creek fault curve southeastward parallel to the lineament as they disappear beneath Miocene basalt (Tabor and others, 1984), so conceivably the lineament marks a tectonic feature that was active during Eocene time. Eocene sedimentary rocks in Washington show maximum thicknesses, about 15,000-29,000 ft, in the fault-controlled basins adjacent to the Straight Creek fault and related faults. If the Olympic-Wallowa lineament follows a continuation of the Straight Creek fault, then more fault-controlled basins might lie along it under the basalt. Eocene sedimentary rocks are thinner, typically between 3,000 and 14,000 ft, in the Puget Lowland and Coast Ranges west of the zone of Eocene faulting in the Cascades, although it is possible that the western edge of the Eocene continental margin sedimentary prism may have been removed and transported northward along another strike-slip system as suggested by Johnson (1984b). East of the Cascades, Eocene sedimentary rocks may form an east-thinning wedge beneath the basalt. This apparent pattern of distribution permits a hypothesis that in Washington, unlike Oregon, there were no well-established through-going fluvial systems to transport sediment westward to the coast across the Eocene zone of fault-controlled uplifts and basins. Perhaps a significant amount of the detritus eroded from unroofing extensional terranes in northeastern Washington and adjacent areas was trapped, along with more locally derived sediment, in the zone of fault-controlled basins along the Straight Creek system and, speculatively, in similar basins along the Olympic-Wallowa lineament.

Eocene or Oligocene fluvial sandstones analogous to the Roslyn, Chumstick, and Wenatchee Formations would be the most likely reservoir rocks in any sub-basalt fault-controlled basins. Limited data from Swauk and Chumstick outcrops suggest porosity and permeability are inadequate (V.A. Frizzell and others, written commun., 1985), but Lingley and Walsh (1986) reported marginally adequate porosity from sandstone samples from recent drill holes spudded in basalt. Barnett (1985) also reported that Roslyn sandstone is poorly cemented. Zeolitized plagioclase grains are abundant in exposed Eocene sandstones (Pongsapich, 1970; Frizzell and others, written commun., 1985), a characteristic that may detract from reservoir potential. Lacustrine mudstones are common in fault-bounded basins and occur in the Chumstick and Swauk Formations (Roberts, 1985; Taylor and others, 1987), so they are likely to be present in any sub-basalt basins and could act as source rocks for gas if they contained enough organic matter. Those in the Nahahum Canyon Member of the Chumstick Formation in the Chiwaukum graben are reported to have some potential as gas source rocks (V.A. Frizzell and others, written commun., 1985; D.E. Anders, oral commun., 1987). Traps could be structural, formed by either Eocene or Miocene and younger deformation, or stratigraphic. Seals would be formed by fluvial or lacustrine mudstone or by basalt. Migration probably began in the oldest parts of graben-filling sequences in Oligocene time, but most of the sequence should have matured only after burial by Columbia River Basalt. These conclusions are based on the results of Lopatin modeling (fig. 8) using vitrinite data for the Shell wells published by Lingley and Walsh (1986), a geothermal gradient similar to the present-day one, and burial histories without any significant erosional intervals.

Outside any fault-controlled basins buried by basalt, petroleum is most likely to be reservoired in Eocene arkosic fluvial sandstones. Such rocks are present in many parts of north-central Oregon, although they are discontinuous and typically fairly thin, from a few hundred feet or less to a maximum of about 2,000 ft in the Blue Mountains anticlinorium near Heppner (fig. 6). Gravity lows immediately north of the Blue Mountains anticlinorium (Riddihough and others, 1986) could imply the presence of thicker accumulations of this sequence beneath volcanic rocks (fig. 2). In eastern Washington, the presence of Eocene sedimentary rocks east of the projected trace of the Entiat fault (eastern boundary of the Chiwaukum graben) has not been proven, but the west-thickening wedge of sedimentary rocks beneath the basalt of the northeastern Plateau interpreted from magnetotelluric data by Stanley (1984) seems most likely to be Paleocene, Eocene, or Oligocene, because known Upper Cretaceous sedimentary rocks in Washington are limited to the Methow and Nanaimo basins flanking the North Cascades. This sedimentary wedge is at least several thousand feet thick if the magnetotelluric interpretation is correct. It seems most likely to be composed of unknown proportions of arkosic detritus and volcaniclastic material; depositional environments were probably fluvial. In the central Cascades, eruptive centers for volcanic units interbedded in the arkosic sequence are concentrated toward the western part of the exposed sequences (see Tabor and others, 1983, 1984, and Frizzell and others, 1984) and less volcanic material is reported from the more easterly of the two Shell basalt-penetrating wells for which subsurface stratigraphic interpretations are available (Campbell and Banning, 1985). These

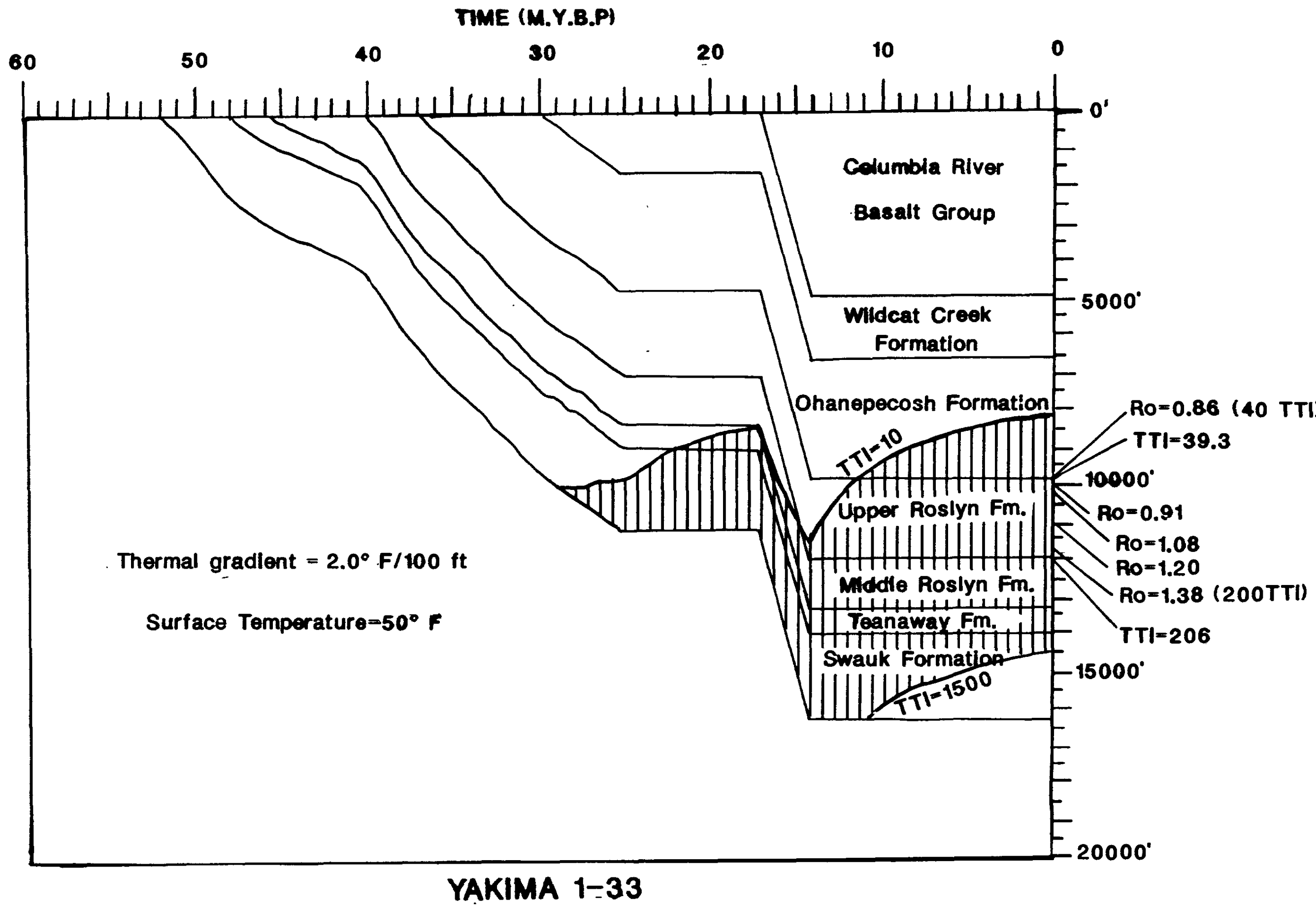

Figure 8.--Burial history plot for Yakima 1-33 well, with superimposed maturation history using an "oil window" of TTI=10 (equivalent to R_o value of 0.6) to TTI=1500 (equivalent to R_o value of 2.2, upper limit for occurrence of wet gas). Surface temperature assumed is 50°F, with a geothermal gradient of 2.0°F/100 ft, slightly lower than the gradient observed in deep drill holes (Montgomery, 1985; Lingley and Walsh, 1986). No erosional removal is assumed; horizontal segments of burial history curves represent non-deposition. This combination of burial history, surface temperature, and geothermal gradient, when used as input for calculation of present-day TTI values according to Lopatin's method, results in TTI values consistent with R_o values reported by Lingley and Walsh (1986). The results suggest that Swauk Formation sediments could have begun to mature about 30 m.y.b.p., but the Roslyn Formation remained immature until it was buried by 5,000 ft of Miocene basalt. (No special thermal effects were modeled for the basalt; it was treated as a "cold" unit.)

relationships might imply an eastward decrease in the volcaniclastic component within any Eocene section beneath the Columbia Plateau, unless the Republic graben of northeastern Washington, which contains a thick accumulation of Eocene volcanic rocks, extends southward under the Plateau. Fluvial sands of reservoir quality beneath the central Columbia Plateau in southeastern Washington could be prospective for gas if adequate coal or organic-rich fluvial or lacustrine mudstone is interbedded with the sandstone. Burial by Columbia River Basalt, in combination with a relatively high regional geothermal gradient, should be adequate to have matured organic matter if it is of sufficient quality and abundance.

In north-central Oregon, Eocene fluvial sandstones could contain gas generated from interbedded coal or carbonaceous mudstone. They could also contain gas or oil generated from Cretaceous marine organic-rich mudstones. Surface outcrops of Cretaceous rocks contain marginally sufficient amounts of Type III organic matter suitable for gas generation (Law and others, 1984a). Sidle and Richers (1985) report that source rock and soil gas studies suggest the presence of both mixed-marine and terrestrial organic matter in the subsurface, indicating the possibility of oil as well as gas. Cretaceous sandstones are reported to have very poor reservoir characteristics (Riddle and Fisk, 1987).

Summary of Plays

PLAY: NORTHWESTERN COLUMBIA PLATEAU

Location: South-central Washington: parts of Yakima, Kittitas, Grant, Franklin, Walla Walla, and Baxter Counties

Estimate of federally controlled land: 60% (including Indian lands)

Play description:

Source rocks.--Gas-prone Eocene lacustrine and fluvial shales and coal beds are potential source rocks. TOC values are: 0.45% (0.03-1.10) in the Swauk Fm.; 0.92-17.09% in the Roslyn Fm.; 1.48% (0.13-5.97%) in the Chumstick Fm. Organic matter is mostly Type III. R_o values in exposed rocks (0.82-1.29 Swauk Fm.; 0.45-1.38 Roslyn Fm.; 0.25-0.89 Chumstick Fm.) suggest that maturity should be adequate beneath the basalt, as does data from subsurface samples (Lingley and Walsh, 1986).

Timing and migration.--Maturation could have begun during the Oligocene in the lean early Eocene section; it was probably middle Miocene and later in middle and late Eocene section, following burial by Columbia basalt. These conclusions are based on Lopatin modeling (fig. 8) and on the observation that sedimentary interbeds in lowermost basalt are marginally mature (T. Walsh, Washington Dept. Natural Resources, oral commun., 1987).

Reservoirs.--Eocene (Swauk, Roslyn, Chumstick) or Oligocene (Wenatchee) fluvial sandstones are the most likely reservoirs. They are 4,000-7,000 ft thick based on drilling, and 20,000 ft or more based on outcrops in the Chiwaukum graben and Swauk basin. Sandstone accounts for only part of these thicknesses. Porosity in Shell deep wells ranged up to 13-16% in tested zones (Lingley and Walsh, 1986).

Traps and seals.--Seals could be formed by Eocene/Oligocene fluvial or lacustrine shales or Columbia River basalt flows. Structural traps could be Eocene, Oligocene, Miocene, Pliocene, or Quaternary folds. Stratigraphic traps could be present in fluvial sequences. Stratigraphic traps might occur at the edge of Pasco basin if it existed as a topographic feature prior to basalt eruption.

Depth of occurrence.--Best shows so far have been at about 13,000 ft in lower Oligocene(?) and middle or upper Eocene rocks. The Rattlesnake Hills gas field (1.3 bcf) produced from a sedimentary interbed in basalt at 700-1,200 ft.

Exploration status.--Rattlesnake Hills gas field (1920's-1940's) is estimated to have produced a total of 1.3 bcf. Five deep tests have been drilled since the 1950's; four penetrated the base of the basalt. Shows in the recent Shell wells included 5-6 MMCFGPD of gas and 6 barrels of condensate per day (Lingley and Walsh, 1986).

Resource potential: Lingley and Walsh (1986) estimated that large anticlinal traps could each contain 40 BCF to 1 TCF of gas. There are about ten of these large folds.

PLAY: NORTH-CENTRAL OREGON
Location: Parts of Wasco, Sherman, Gilliam, Morrow, Umatilla, Union, Grant, Wheeler, and Crook Counties
Estimate of federally controlled land: 40%
Play description:

Source rocks.--Cretaceous marine shales are the most probable source rocks. TOC values are 0.68-1.18% in the Bear Creek well (Albian?) according to Newton (1979), over 2% in the Albian-Cenomanian sequence in the Mitchell inlier (Sidle and Richers, 1985), or 0.21-1.44% according to Law and others (1984). Sidle and Richers (1985) reported that TOC increases to the northwest, organic matter is both mixed marine and woody-herbaceous, maturity is within the oil window, and soil gas studies show NE-trending anomalies, which they correlated with probable Cretaceous source rocks in the subsurface.

Timing and migration.--Paraffinic oil in a geode from the Clarno Formation indicates generation is post-Eocene. Thickness is probably inadequate for generation without burial by Clarno-John Day-Columbia basalt sequence. Summer and Verosub (1987) suggest that a geothermal event about 22 m.y.b.p. caused maturation in the Bear Creek well.

Reservoirs.--Maestrichtian(?)-Paleocene(?) fluvial-deltaic sandstones in the Ochoco sequence are quartzose, permeable, friable, and 300 ft thick. A Paleocene(?)-Eocene fluvial sandstone, mudstone, and coal sequence in the Blue Mountains is about 2,000 ft thick. A 600-ft-thick shale-dominated interval with several possible friable sandstone beds 2-12 ft thick is present in the Northwest Morrow well based on the log analyst's report. Sandstone is also interbedded with the Eocene Clarno volcanics. Albian-Cenomanian sandstones have poor permeability and porosity of only about 8% in outcrop but may improve at depth, based on log analysis (Fritts and Fisk, 1985b).

Traps and seals.--Miocene and younger folds could provide structural traps; stratigraphic traps are possible in fluvial-deltaic sequences. Fluvial-deltaic shale and Eocene-Miocene volcanic rocks are the most probable seals.

Depth of occurrence.-- The early Tertiary potential reservoir sequence is typically encountered at about 2,000-3,000 ft in the subsurface. In the Kirkpatrick well north of Blue Mountains, the potential reservoir sequence is thin or absent but the base of the overlying John Day Formation is at a depth of over 6,000 ft, suggesting a paleo low and/or subsequent deformation. If the early Tertiary potential reservoir sequence is locally present north of the Blue Mountains, it would be at significantly greater depths than it is southeast from the Blue Mountains.

Exploration status.--About 14 wells have been drilled with a few shows of gas or oil; useful data are available from about half of the wells.

AREA 2, EASTERN CASCADE RANGE OF CENTRAL WASHINGTON

Description

The Chiwaukum graben (fig. 2) is a pull-apart basin containing a thick section of Tertiary nonmarine sediments. The Chumstick Formation, which is the principal graben-fill unit, is at least 19,000 ft (Whetten, 1976) and possibly over 29,000 ft thick (Evans, 1987). The graben is bounded by the Entiat Fault on the east and the Leavenworth fault on the west. The Swauk basin (Tabor and others, 1984; Johnson, 1985) lies west of the Leavenworth Fault and east of the Straight Creek Fault (Fig. 2). Sediments in the Swauk basin were possibly originally continuous with the Chuckanut Formation and offset by syndepositional or immediately post-depositional movement along the Straight Creek Fault (Gresens and Stewart, 1981; Johnson, 1985).

The Swauk basin and Chiwaukum Graben have different subsidence histories. The Swauk basin is somewhat older. The lower Eocene Swauk Formation apparently mostly predates the middle Eocene Chumstick Formation which fills the Chiwaukum graben; it is equivalent to the lower part of the Chuckanut Formation (Gresens and others, 1977; Yeats, 1977; Johnson, 1985). The Swauk Formation is overlain by andesite and basalt of the Teanaway Formation and sandstone and minor rhyolite of the Roslyn Formation. The lower part of the middle and upper Eocene Roslyn formation is equivalent to the upper parts of the Chuckanut and Chumstick Formations, and the upper part of the Roslyn is equivalent to the Huntingdon Formation (Johnson, 1985). The Oligocene Wenatchee Formation unconformably overlies the Chumstick Formation (Gresens and others, 1977). The thickness of the Swauk Formation is about 15,000 ft (Tabor and others, 1984), the Teanaway Formation is 30 to 8,000 ft thick (Tabor and others, 1984), and the Roslyn Formation is 8,500 to 9,000 ft thick (Walker, 1980; Barnett, 1985). Total thickness in the Swauk basin thus exceeds 20,000 ft; the Chumstick Formation in the Chiwaukum graben is as much as 29,000 ft thick.

All units are fluvio-lacustrine in origin. The Chumstick Formation consists primarily of sandstone and conglomerate with minor interbedded tuffs. Lacustrine shales of the upper part of the Chumstick Formation (Nahahum Canyon Member) are dark gray and organic-rich in places. The Swauk and Roslyn Formations consist largely of fluvial sandstone conglomerates, and carbonaceous shales. The Roslyn Formation also contains coal beds (Glover, 1936; Tabor and Frizzell, 1977). The Wenatchee Formation consists of tuffaceous shale, sandstone, conglomerate, and paleosols (Gresens and others, 1981; Hauptmann, 1983). This unit has been identified specifically as a suitable reservoir rock (Gresens and Stewart, 1981) in that it is relatively thick (900 ft in places) and porous. Lacustrine shales in the lower part have been described as "local" and organic-rich, presumably with terrestrial plant debris (Gresens, 1977; Gresens and others, 1981); they contain evidence of burrowing activity (Hauptmann, 1983), so the environment was evidently not oxygen-poor. Sands in the Chumstick and Swauk exhibit widespread zeolitization (Pongsapich, 1970), which potentially detracts from their reservoir quality. The Swauk was folded shortly after deposition and then intruded by feeder dikes for extrusive rocks of the unconformably overlying Teanaway Formation (Tabor and others, 1984). The Teanaway and Roslyn Formations are significantly less deformed than the Swauk Formation.

Oil shows have been reported near Wenatchee (Glover, 1936; Wagner, 1966) and a well drilled there (Norco No. 1, bottoming in Swauk) had gas and oil shows (Wagner, 1966; McFarland, 1982). Two wells drilled in the southernmost Chiwaukum Graben near the edge of Miocene basalt have had gas shows; one well reached 900 ft, the other penetrated to 4,700 ft.

Donald E. Anders (oral commun.) has performed organic geochemical analyses on samples from the Swauk, Chumstick, and Roslyn Formations. The Swauk values were 0.03-1.1 wt.% TOC (mean, 0.45%), Chumstick 0.13-5.97% TOC (mean, 1.48%; mostly Nahahum Canyon Member), and Roslyn 0.92% (one sample; Anders also analyzed a coaly bed, which had 17% TOC). Thus, the lacustrine facies of the Chumstick Formation appears to contain the best source rocks. With one or two exceptions, the samples contained type III organic matter, which is most likely to yield gas. The rocks generally show low thermal maturity. Hammer (1934) proposed coals in the Roslyn Formation as the sources for the gas in the Rattlesnake Hill gas field (see Area 1 discussion). Montgomery (1985) concluded that the sandstone units of this area have the best potential as reservoirs for hydrocarbons in the Columbia Plateau region.

Summary of Plays

PLAY: EAST-CENTRAL CASCADE RANGE
Location: Chelan and Kittitas Counties, Washington
Estimate of federally controlled land: 60%
Play description:

Source rocks.--The upper part of the Chumstick Formation consists of approximately 2,000 ft of lacustrine sediments; average organic carbon value is 1.5%. The Roslyn Formation contains bituminous coals, which might be sources for gas.

Generation, timing, migration.--Any generation probably would have been latest Eocene or younger. Maturation would most likely have begun during burial of the deeper parts of the section by Wenatchee or Roslyn-equivalent rocks, so it is questionable whether the more organic-rich facies, which are higher in the section, reached sufficient burial depths. Available vitrinite reflectance data suggest that most of these rocks are marginally mature at best.

Reservoirs.--The Chumstick contains fluvial sandstones that could act as reservoirs; the Wenatchee is a porous, friable sandstone that has been described as an excellent potential reservoir. The Roslyn Formation is fluvial; it contains lenticular sandstones that might be suitable reservoirs. Porosity is generally low in the Eocene sandstones (V.A. Frizzell and others, written commun., 1983); many exhibit zeolitization.

Traps and seals.--Traps would be stratigraphic in the very gently-dipping parts of the Roslyn and structural or stratigraphic in most of the area, formed by Eocene-early Oligocene folds. Seals would presumably be floodplain shales or possibly volcanic rocks. The Wenatchee might be sealed by overlying Miocene shales (Gresens and Stewart, 1981).

AREA 3, NORTHWESTERN CASCADE RANGE, WASHINGTON

Description

In western Whatcom and Skagit Counties on the west slope of the North Cascades, there are several isolated occurrences of Paleogene sedimentary rocks overlying pre-Cenozoic basement and interbedded with volcanic rocks (Johnson, 1984a; Johnson, 1985). The principal sedimentary units are the Eocene Chuckanut Formation, more than 19,000 ft thick, and the overlying Huntingdon Formation, which were deposited in a fluvial setting. The units comprise sandstone, highly carbonaceous (terrestrial plant material) shales, conglomerate, and coal. No evidence exists for marine incursions in this section.

Several dozen wells have been drilled in this area, with completions as recently as 1977 (McFarland, 1982). Gas flowed from Pleistocene gravels in several wells at about 170 ft and from the Chuckanut(?) at about 1,000 ft in one well (which also produced from Pleistocene strata). Several wells have been drilled to depths greater than 1,000 ft. Many wells had gas shows, and oil shows also were reported from a few wells. Oil seeps reported in Bellingham (Glover, 1935) may be suspect. Several wells in western Whatcom County have had enough gas for domestic use, many producing from depths <500 ft (Glover, 1947; McFarland, 1982). No wells in Skagit and Snohomish Counties had enough gas even for domestic use. Wells in western Skagit County have bottomed in schist at <1,000 ft; all have been dry (McFarland, 1982).

The coal and carbonaceous shale of the Chuckanut Formation could be the sources for the gas. Together, the carbonaceous shales and coals form a small part of the section, and the thickest coal bed is 14 ft (Glover, 1935). Coal rank near the surface is low bituminous to sub-bituminous (Glover, 1935). This raises the possibility that the gas may be biogenic, consistent with its high methane and nitrogen content (Wagner, 1966). We could find no organic geochemical analyses for the shales. Clearly, more information is needed before the source rocks for gas and oil shows can be confidently identified.

Potential reservoirs in sandstone and conglomerate occur throughout the section. The Chuckanut Formation does not appear to be buried except under glacial deposits, so the maximum depth would be about 20,000 ft.

Summary of Area 3

PLAY: CHUCKANUT
Location: Western Whatcom, Skagit, and Snohomish Counties, Washington
Estimate of federally controlled land: <1%
Play description:

Source rocks.--Coals, which range from a few inches to 14 ft in thickness, and carbonaceous shales are the most likely source rocks.

Generation, timing, and migration of hydrocarbons.--Gas shows in Pleistocene sediments imply that generation has taken place during Quaternary time or that older trapped hydrocarbons are leaking into young traps, if gas is not biogenic. Eocene burial would have to have been sufficient to mature the older Eocene rocks because no post-Eocene burial episode is evident from the regional stratigraphy.

Reservoirs.--Fluvial sandstones and conglomerates are the most likely reservoir rocks.

Traps and seals.--Traps in the Pleistocene cover are random and not apparently related to surface features, so they are probably stratigraphic (Glover, 1935). Seals are probably clay-rich beds (glacial lacustrine sediments?). Traps in the Tertiary rocks are likely to be stratigraphic, as the sediments are fluvial, including braided-stream deposits (e.g., Johnson, 1984); in Whatcom County, structural traps could occur in north- and northeast-trending anticlines (Glover, 1935), formed during Eocene deformation.

Depth of objective.--The Chuckanut Formation in Whatcom County is over 19,000 ft thick and underlies 0-350 ft of Pleistocene cover.

AREA 4, CENTRAL OREGON

Description

Marine and terrestrial rocks of Cretaceous, Paleocene(?), Eocene, and Oligocene age crop out in the western part of the Blue Mountains anticlinorium (Hudspeth, Gable Creek, Clarno, and John Day Formations and the informally named "Herren Formation"). The Tertiary units are roughly equivalent to the Swauk-Chumstick-Roslyn-Wenatchee nonmarine sedimentary and volcanic sequence northwest of the Columbia Plateau. Unlike the rocks in Washington, however, the Clarno and John Day Formations are composed principally of volcanic and volcaniclastic rocks (Baldwin, 1981; Robinson and others, 1984), with a subordinate component of fluvial sediment.

Early Tertiary fluvial or deltaic arkosic sandstones interbedded with coal and shale, the "Herren Formation," are widespread throughout north-central and northeastern Oregon, although they are generally fairly thin and sometimes absent. These rocks lie beneath the Clarno volcanics and above either Upper Cretaceous sedimentary rocks or pre-Cretaceous rocks of the Blue Mountains island arc complex. The thickest section, about 2,000 ft, crops out along the Blue Mountains anticlinorium, where it rests with angular unconformity on Blue Mountain accreted arc rocks. It has been described by Pigg (1961), Shorey (1976), and Ferns and Brooks (1986) as a sequence of sandstone with carbonaceous shale and coal interbeds; some sections contain interbedded volcanic rocks, particularly upsection. Sandstones exhibit massive bedding or cross bedding and are generally feldspathic, medium to coarse-grained, well-indurated to friable, matrix-poor, and zeolitic. Sediment transport was toward the northwest. Interbedded lignitic coal seams and carbonaceous shale beds are typically a few inches to about 8 ft thick (Mendenhall, 1909; Ferns and Brooks, 1986). Plant fossils indicate Paleocene (Gordon, 1985) and early to middle Eocene ages (Pigg, 1961; Hogenson, 1964; Shorey, 1976) and a subtropical or warm temperate climate; the assemblage is very similar to that in the Chuckanut Formation in northwestern Washington (Gordon, 1985).

Heller and others (1985) inferred an Idaho batholith provenance based on similarity of isotopic data from micas, feldspars, and whole-rock samples of "Herren" sandstones with Idaho batholith granitic rocks. Such a provenance corresponds neatly with latest Cretaceous-earliest Tertiary unroofing of the Idaho batholith required by the unconformity between Upper Cretaceous plutonic rocks and the overlying Eocene Challis volcanics. Heller and others (1985) also infer that the Blue Mountains area was much closer to the Idaho batholith in the early Tertiary and was subsequently moved westward during clockwise rotation inferred from paleomagnetic data (Wells, 1984; Grommé and others, 1986).

Rocks similar to but thinner than the "Herren" unit exposed in the Blue Mountains have been reported from other localities throughout north-central Oregon. Very few details are available concerning their lithology, stratigraphy, or age, but, taken together, they suggest that deposition of arkosic sediment in some sort of extensive fluvial system which drained the Idaho batholith may have been widespread between the end of Cretaceous time and the beginning of Clarno volcanism in the Eocene. Collier (1914) mentioned "a great thickness of sandstone, shale, and conglomerate which rests upon serpentine" northwest of the town of John Day in an area (T13S, R31E, section 15) shown as Clarno Formation by Walker (1977). According to Pigg (1961), M.S. theses by Mobley (1956) and Nelson (1956) reported Tertiary chert pebble conglomerate and lower Tertiary conglomerate in the area west of Bates and north of Prairie City, eastern Grant County. Walker (1973) mapped a sequence similar to the "Herren" unit in northeastern Wheeler County. In the Northwest Morrow No. 1 well between Prineville and Madras in southeastern Jefferson County (fig. 4), well reports indicate a sequence of shale, friable sandstone, siltstone, lignitic coal, and bituminous shale 600 ft thick beneath 2,500 ft of volcanic rock. In the Texaco Federal No. 1 well south of Mitchell in Crook County, over 500 ft of "Maestrichtian to Paleogene" nonmarine section is reported by Thompson and others (1984) based on pollen; the lithologies retrieved by sidewall cores in this interval include white, friable, fine-grained, quartzose sandstone with good permeability, dark volcanic rock, and light gray siltstone with quartz grains, according to well records. These early Tertiary sandstones could be suitable reservoir rocks, but not enough is known yet about early Tertiary sediment transport patterns to make inferences about distribution and facies with any confidence.

The most extensive exposure of Cretaceous rocks is near Mitchell, Oregon. The Hudspeth Formation (Albian-Cenomanian) consists of outer submarine fan turbidites interfingering with inner-fan channel sands and conglomerates of the Gable Creek Formation (Kleinhans and others, 1984). These units unconformably overlie accreted early Mesozoic and Paleozoic rocks. The section is as much as 8,800 ft in thickness. Law and others (1984a) analyzed samples of the Hudspeth and Gable Creek Formations from Wheeler County. Total organic carbon (TOC) values ranged from 0.21-1.44 wt. percent, and vitrinite reflectance measurements indicated that the rocks are barely thermally mature. The organic matter is all type III kerogen, suggesting that these rocks would be more likely to have generated gas than oil. Sidle and Richers (1985), however, presented data from pyrolysis, solvent extraction, and soil-gas studies which they interpreted as suggestive of mixed-marine organic matter in the source rocks, possibly capable of generating paraffinic oil.

Upper Cretaceous section of the "Ochoco basin" has been penetrated in the subsurface about 30 miles south of the Mitchell area outcrop of the Hudspeth and Gable Creek Formations. Presumably the two sequences are continuous in the subsurface. Thompson and others (1984) report biostratigraphic data from four wells (three of which are shown on fig. 9) which indicate the presence of Albian to Campanian sediments deposited at outer neritic to bathyal depths, overlain in one well by by nonmarine Maestrichtian-Paleogene section. Younger Tertiary volcanic section overlies the Cretaceous sequence in all of these wells. Maximum thickness of the Cretaceous in these wells is about 4,000 ft, not 4,300 m as reported by Nilsen (1984a). The bulk of the Cretaceous section is Albian-Cenomanian and lithologies are predominantly mudstone. One well (Texaco Logan Butte) contains a fairly complete Upper Cretaceous section about 2,000 ft thick. Limited information suggests that gas source rocks might be present. TOC values range from 0.76 to 1.18 in Albian-Turonian section in the only well (Sunray Bear Creek) for which organic geochemical

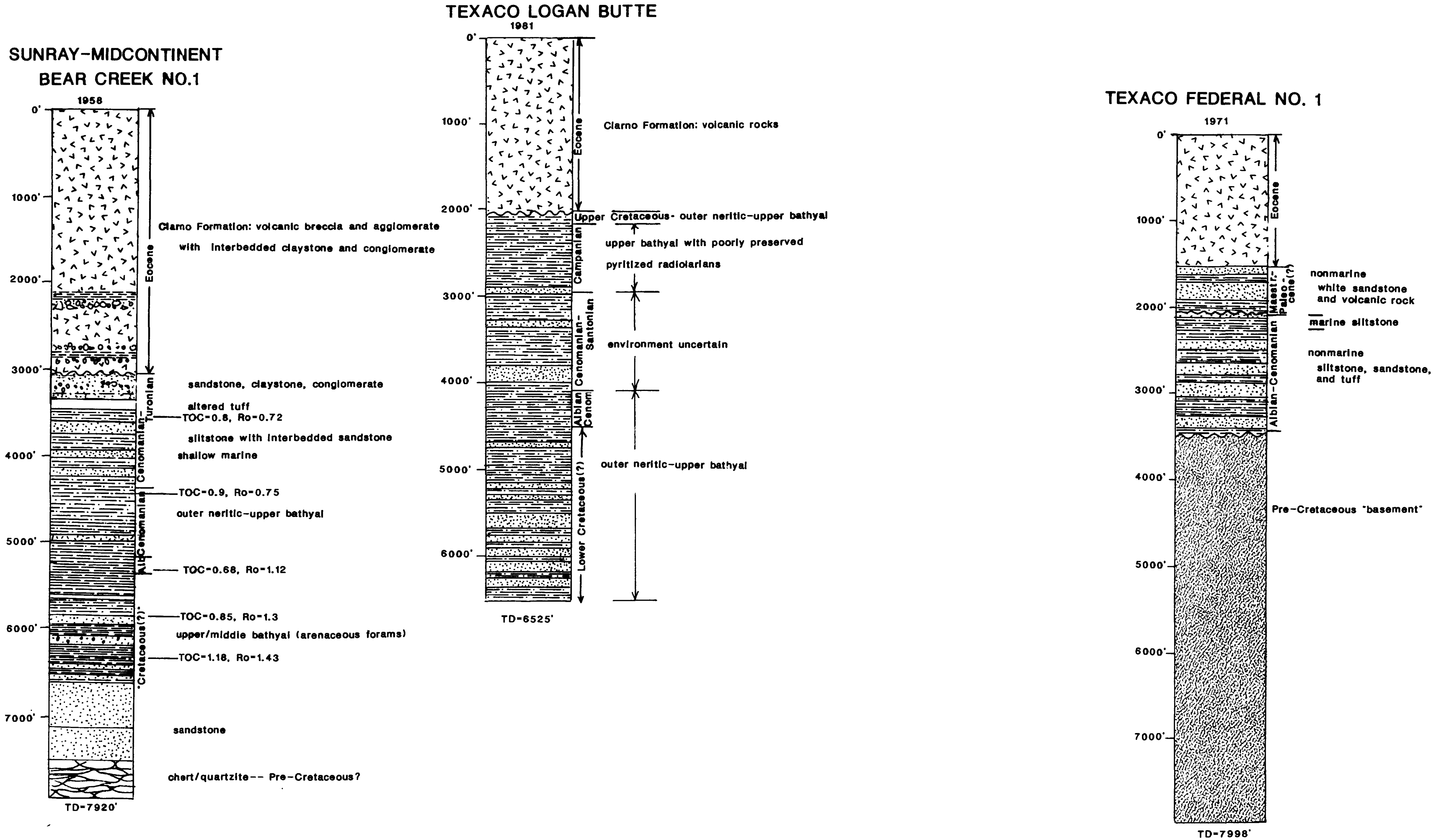

Figure 9.--Stratigraphy for 3 wells in Ochoco basin region of central Oregon. Data compiled from Thompson and others (1984), Newton (1979), and well reports. Columns placed to indicate relative elevations and lateral spacing. Lithologies shown are interpretive or uncertain in many cases.

data are available (Newton, 1979); R_o values range from 0.72 to 1.43, with an abrupt increase near the top of Albian-Cenomanian section, also reported qualitatively within Cenomanian section in one other well (Thompson and others, 1984). Newton's (1979) analyses indicate that organic matter in the Sunray Bear Creek is virtually all terrestrial, and may be largely oxidized. Summer and Verosub (1987) have proposed that the R_o profiles observed in two of these wells can be explained by a hydrothermal "event" in late Oligocene or early Miocene time which matured the whole section to about the same degree; they think this event was probably related to eruption of the overlying volcanic cover.

Nilsen (1984a,b) proposed that the Hudspeth Formation and the Ochoco section and the west-derived Hornbrook Formation of southwestern Oregon were deposited on opposite sides of a forearc basin, the Hornbrook-Ochoco basin, which was similar to but wider than the Great Valley forearc basin of California and possibly contiguous with it. If this was the case, the widespread occurrence of gas in the Sacramento Valley lends some support to the potential for hydrocarbons in Cretaceous rocks beneath the volcanic cover of central Oregon. Differences between the Eocene rocks of the two areas are significant (volcanics and fluvial sediments in Oregon vs. deltaic and submarine fan channel sediments in the Sacramento Valley).

Rocks older than Cretaceous in the Blue Mountains consist of island arc and subduction complex rocks that were welded to the continent in the Early Cretaceous (Dickinson and Thayer, 1978; Davis and others, 1978; Pessagno and Blome, 1986; Vallier, 1986; Vallier and Brooks, 1986; Mann and Vallier, 1987). Late Triassic to Middle Jurassic rocks of the Izee terrane overlying Early Triassic and Paleozoic structurally disrupted rocks of the Grindstone terrane (Silberling and others, 1984; Blome and others, 1986) are highly deformed and generally have been regarded as too mature for hydrocarbons (e.g., Montgomery, 1985; Dickinson and Thayer, 1978, described them as weakly metamorphosed). However, Law and others (1984a) found vitrinite reflectance values as low as 0.34 for even the Triassic rocks. Unfortunately, some of these determinations are not accompanied by TOC analyses. In easternmost Oregon, one sample of "Jurassic-Triassic argillite" contained 1.22% TOC (Law and others, 1984a). The sample probably came from Lower or Middle Jurassic rocks of the Weatherby Formation in the Olds Ferry Terrane, where Jurassic marine sedimentary rocks unconformably overlie Upper Triassic volcanic rocks from an island arc setting (Blome and others, 1986). An important problem with these accreted terranes is the probable lack of reservoir rocks; lithologic descriptions generally imply that pre-Cretaceous sandstones lack porosity and permeability, although actual measurements are unavailable.

Summary of Plays

PLAY: OCHOCO-MITCHELL

Location: Wheeler, Crook, Jefferson, and Deschutes Counties of central Oregon

Estimate of federally controlled land: 75%

Play description:

Source rocks.--Organic-rich, laminated black shales of middle Cretaceous or Jurassic age, or early Tertiary coal or fluvial shales are the most promising source rock candidates.

Generation, timing, and migration.--Generation of hydrocarbons from early Tertiary rocks possibly would have begun during the late Oligocene when hot fluids from volcanic eruptions might have matured the section (Summer and Verosub, 1987). Otherwise, local thick accumulations of Clarno and John Day volcanics might have buried the early Tertiary enough to cause maturation. Data are insufficient to permit reconstruction of maturation history in pre-Tertiary rocks.

Traps and seals.--Traps could be stratigraphic or structural (folds and/or faults), and seals intraformational shales.

Reservoirs.--Hydrocarbons generated in the Hudspeth Formation might be reservoired in the intertonguing Gable Creek Formation, in which porosity and permeability are poor in outcrop, or in overlying Tertiary rocks, which are generally volcaniclastic but include fluvial arkosic sequences.

AREA 5, SOUTHWESTERN OREGON AND MODOC PLATEAU

Description

The Hornbrook Formation, a transgressive sequence of Upper Cretaceous marine clastic sediments, lies unconformably on the eastern flank of the Jurassic and older Klamath accretionary complex in southwestern Oregon and northern California. This northeast-dipping homoclinal sequence is about 4,300 ft thick and is overlain locally by late Eocene nonmarine sandstone and conglomerate of the informally-named Payne Cliffs Formation (McKnight, 1984), about 7,500 ft thick, and regionally by Eocene and Oligocene volcanic and volcaniclastic rocks of the Western Cascades Group. The eastward extent of the Hornbrook and Payne Cliffs Formations beneath the Cascades volcanics and volcanics of the Modoc Plateau in northeastern California is uncertain; seismic refraction (Fuis and Zucca, 1984; Fuis and others, 1987) and gravity modeling studies (Erskine and others, 1984) indicate the possibility of significant thicknesses of Hornbrook-equivalent sedimentary rocks beneath the Tertiary volcanic cover. The refraction work suggests that Upper Cretaceous and Cenozoic rocks overlying presumed Sierran-type basement beneath the Modoc Plateau constitute a layer up to 6 km thick. At least 3 km of the 6 km must be Oligocene and Miocene volcanics, on the basis of the exposed volcanic sequence in the Warner Range just east of the Modoc Plateau (Duffield and McKee, 1986). The gravity modeling study (Erskine and others, 1984) concludes that 16,000 ft of Hornbrook sequence rocks underlie about 15,000 ft of volcanics beneath the eastern Cascades and that no structure at depth is required to account for a regional gravity gradient associated with the eastern margin of the Klamath complex. On the basis of comparison of Hornbrook biostratigraphy with detailed biostratigraphic work in the northernmost Sacramento Valley, however, Haggart (1986) concluded that a significant thickness of Upper Cretaceous section beneath the Modoc Plateau is unlikely. Data are obviously insufficient to resolve the question.

The Hornbrook Formation as described by Nilsen (1984a) consists of about 4,300 ft of Upper Cretaceous mostly marine section; rocks of all the Late Cretaceous stages except the Santonian are present. Nilsen (1984a) divided the unit into several members. The basal Klamath River Conglomerate ranges from 0 to 295 ft in thickness and consists of conglomerate and sandstone deposited in fluvial and alluvial fan environments; it is unfossiliferous except for an Albian-Cenomanian palynoflora reported from outcrops near Yreka, California (Jameossanie and others, 1986). The Cenomanian(?)-Turonian-Coniacian Osburger Gulch Sandstone contains sandstone conglomerate, siltstone, and shale deposited in a shelf environment; it is about 250-500 ft thick. The Ditch Creek Siltstone, also Turonian-Coniacian, consists of shelf-deposited siltstone but also contains a freshwater coal horizon; thickness is 65-260 ft. The Rocky Gulch Sandstone of uncertain but possible Turonian age is a fine- and medium-grained deep marine sandstone 375-740 ft thick. The uppermost unit, the Blue Gulch Mudstone, is a thick (possibly over 2,900 ft) Campanian-Maestrichtian mudstone with siltstone and fine-grained sandstone, deposited in outer shelf and basin-plain environments. It contains two sandy units, one a concentration of sandstone beds within a 275-ft-thick zone, and the other a laterally persistent bed 6-16 ft thick, the Hilt Sandstone Bed. Transport direction in all of these units was generally down a northeast-deepening slope, which suggests that the basin must have extended some distance to the northeast.

Unconformably overlying the Hornbrook Formation is sandstone and conglomerate of the Payne Cliffs Formation of late Eocene age. It was deposited in braided streams and alluvial fans which apparently developed when the Klamath complex was uplifted, shedding sediment to the northeast (McKnight, 1984). Some siltstone, mudstone, coal, and tuff is present near the top of the unit.

Sandstones in both the Hornbrook and Payne Cliffs Formations are typically lithofeldspathic, with an obvious Klamath provenance (Golia and Nilsen, 1984; McKnight, 1984). Payne Cliffs conglomerates contain Hornbrook clasts, which suggests that sands in the Payne Cliffs might be at least partly recycled and potentially cleaner than those in the Hornbrook, although no detailed data on Payne Cliffs sandstone petrology are available. Porosity in Hornbrook sandstones is variable, ranging from 6 to 18% and averaging 11.7% according to Keighin and Law (1984); pores are typically lined with chlorite and/or filled with clay. The Hilt Sandstone in the Blue Gulch Member has the best porosity (18%), but kaolinite tends to fill the pores. Permeability varies from 0.01-1.2 millidarcies. Reservoir potential is thus generally low in the samples studied, although the possibility of better reservoir characteristics in the subsurface cannot be completely ruled out.

There is some evidence to suggest that source rocks suitable for gas generation could be present within the Hornbrook Formation. Analyses by Law and others (1984a) indicate that samples from the Ditch Creek Siltstone and the Blue Gulch Mudstone Members contain 0.5-1.2% TOC; coal in the Ditch Creek Siltstone contains 23.6% TOC. The TOC values measured are probably minimum values because the samples were weathered. Organic matter is Type III on the basis of both visual and chemical analysis. Maturity is marginal; R_o values are 0.4-0.83 and most are less than 0.7. Maturity could increase significantly eastward beneath the western edge of the Cascade volcanic pile, however; burial by the 3-5 km of volcanic and volcaniclastic rocks of the Cascades and Modoc Plateau is probably sufficient to have matured any underlying sediments.

The only significant structures affecting the homoclinally east-dipping Hornbrook-Payne Cliffs sequence are northeast-trending normal faults with their southeast blocks downthrown. They are of middle to late Tertiary age (Nilsen, 1984a) with about 3-6 km offset. Regional tilting began after 20 m.y.b.p. and ended by Pliocene time, demonstrated by flat-lying Pliocene and younger High Cascades volcanics resting unconformably on tilted older rocks. Anticlinal traps are probably unlikely; traps would have to be primarily stratigraphic or fault-controlled.

If indeed a significant sequence of Cretaceous and Eocene sediments extends eastward from the Hornbrook outcrop belt beneath the Tertiary volcanic cover, it probably underwent maturation only as the overlying volcanic rocks accumulated to a substantial thickness, so generation is not likely to have taken place before about Miocene time. Tilting and faulting would probably have begun by that time, providing possible structural traps for any hydrocarbons generated.

Summary of Plays

PLAY: HORNBROOK-MODOC
Location: Jackson and Klamath Counties, Oregon, and Siskiyou County, California
Estimate of federally controlled land: 90%
Play description:

Source rocks.--The Ditch Creek Siltstone and Blue Gulch Mudstone Members of the Hornbrook Formation contain intervals with TOC values between 0.5 and 1.2%, as well as coal in the Ditch Creek Siltstone. There are coaly horizons in the upper part of the Payne Cliffs Formation. Organic matter is all Type III so far as is known; maturity is marginal but could increase eastward beneath volcanic cover.

Generation, timing, migration.--Because there is no evidence that Hornbrook rocks were buried to any significant depths prior to Cascades-Modoc volcanism beginning in the late Eocene or Oligocene, it seems unlikely that generation began before late Oligocene or Miocene time.

Reservoirs.--The Hilt Sandstone Bed of the Blue Gulch Member is laterally persistent and about 6-16 ft thick; it has as much as 18% porosity in samples studied, although pores have kaolinite fillings. The Osburger Gulch Sandstone, the Rocky Gulch Sandstone, another sand-rich interval in the Blue Gulch Mudstone, and sandstone of the Payne Cliffs Formation are other possible reservoir units, although available data indicate poor porosity and permeability in surface samples. Porous volcanic units in the Cascade volcanic pile are theoretically potential reservoirs.

Traps and seals.--Anticlinal traps are probably not present. Traps would have to be stratigraphic or associated with mid-Tertiary normal faults. Seals could be either shales within the Hornbrook or possibly impermeable volcanic units in the Cascades sequence.

AREA 6, SOUTHEASTERN OREGON

Description

Possibly prospective units in this area are late Miocene nonmarine sediments overlying the Columbia River Basalt Group, principally in southern and eastern Oregon, and the Idaho Group, which is Pliocene and Pleistocene in age and overlies the basalt in southeastern Oregon. Southeastern Oregon constitutes the northern portion of the Basin-and-Range province (Dickinson, 1979). In Malheur County, southeastern Oregon, basalts equivalent to those of the Columbia River Basalt Group overlie crystalline basement or late Paleozoic to early Mesozoic metamorphic rocks (Newton and Corcoran, 1963; Kittleman and others, 1965).

The Sucker Creek Formation (Barstovian age, late Miocene) is predominantly volcaniclastic sandstone; some beds are carbonaceous to coaly, but all are local in extent (Newton and Corcoran, 1963). Kittleman and others (1965) interpreted the Sucker Creek to be fluviatile in origin, with minor lacustrine deposition. The Sucker Creek Formation ranges from a few hundred to 2,000 ft thick (Newton and Corcoran, 1963). No wells have penetrated the Sucker Creek Formation itself in Malheur County. In southern Lake County, numerous wells had gas shows that were probably in Sucker Creek equivalents. Humble Oil Co. drilled two wells in Lake County in the early 1960's that bottomed at 9,579 ft and 12,093 ft; both were dry. The Drip Spring Formation (late Barstovian age, late Miocene) of the Owyhee region of southeastern Oregon is about 1,500 ft thick and consists of sandstone, diatomite, and carbonaceous volcanic shales (Kittleman and others, 1965). The Juntura Formation (Clarendonian age, early Pliocene; aggregate thickness about 1,200 ft) and partly equivalent Bully Creek Formation consist of volcaniclastic sandstone and conglomerate and thick diatomites (Kittleman and others, 1965).

The Idaho Group, which occurs in southeastern Oregon (Snake River basin; Vale-Ontario basin of Newton and others, 1962), is at least 5,000 ft thick (Newton and Corcoran, 1963). The group comprises fluvial and lacustrine rocks, including diatomites and thin coals (Newton and Corcoran, 1963). It underlies about 500 ft of late Pliocene to Pleistocene volcanics of the Snake River Group (Newton and Corcoran, 1963; Kittleman and others, 1965).

Gas shows have been found throughout the Idaho Group to a maximum of about 7,000 ft. Wells drilled in northern Malheur County, Oregon, stopped at the Owyhee Basalt, which is as much as 1,500 thick. Many have had continuous flows at low levels, suitable for domestic use. Some wells have blown out or had very strong flow rates (up to 20,000 mcf/d), but these flows lasted for very short periods. Quantity of gas produced is very small. No organic geochemical analyses on the lacustrine sediments were found; coal rank also is not known.

Summary of Plays

PLAY: SOUTHEASTERN OREGON
Location: southeastern Lake County, Harney and Malheur Counties
Estimate of federally controlled land: 85%
Play description:

Source rocks.--Thin coals and lacustrine carbonaceous shales and diatomites are potential source rocks.

Generation, timing, and migration.--Gas shows have been in the Idaho Group, where generation must have been post-Pliocene.

Reservoirs.--The rocks are generally fluvial, comprising much sandstone and conglomerate with considerable pyroclastic material. Sandstones are friable in places, implying high porosity, and are lenticular. Reservoirs are as shallow as a few hundred feet but also apparently small in extent.

Traps and seals.--Traps are stratigraphic, but some fault traps could possibly exist. Small anticlines occur throughout the region. Seals are fluvial shales and claystones; seals on the basalts are lacustrine shales (Newton and Corcoran, 1963). Much of the terrane is dissected by erosion, so that many traps could have been breached.

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