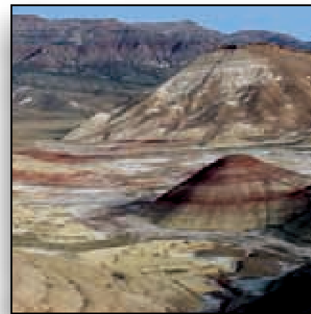
Chapter 2

Cretaceous-Tertiary Composite Total Petroleum System and Geologic Assessment of Undiscovered Gas Resources of the Eastern Oregon and Washington Province



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By Michael E. Brownfield

Chapter 2 of
Geologic Assessment of Undiscovered Gas Resources of the Eastern Oregon and Washington Province

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

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Cretaceous-Tertiary Composite Total Petroleum System and Geologic Assessment of Undiscovered Gas Resources of the Eastern Oregon and Washington Province

By Michael E. Brownfield

Abstract

The U.S. Geological Survey (USGS) assessed the undiscovered natural gas resources of the Eastern Oregon and Washington Province, which includes about 60,000 square miles in eastern Oregon and Washington. The assessment of the Eastern Oregon and Washington Province was geology-based and applied the total petroleum system (TPS) concept. The geologic elements of a TPS include hydrocarbon source rocks (source rock maturation and hydrocarbon generation and migration), reservoir rocks (quality and distribution), and traps for hydrocarbon accumulation. Using these geologic criteria, the USGS defined the Cretaceous-Tertiary Composite Total Petroleum System and three assessment units (AU) within it: (1) the Columbia Basin Continuous Gas AU; (2) the Eastern Oregon and Washington Conventional Gas AU; and (3) the Republic Graben Gas AU. Undiscovered gas resources within the first two were quantitatively estimated; the Republic Graben Gas AU was not assessed.

Volcanic rocks in the Miocene Columbia River Basalt Group, which range in thickness from 4,000 feet to more than 15,000 feet, overlie a nonmarine sedimentary rock succession in much of the Eastern Oregon and Washington Province. Some 5,000 feet to 10,000 feet of Paleogene volcanic rocks, arkosic sandstone, mudstone, lacustrine shale, and coal are present below the basalt in north-central Oregon and central Washington. These rocks include potential mature source and reservoir rocks.

The USGS assessed both undiscovered conventional gas and undiscovered continuous (unconventional) gas resources, resulting in an estimated mean total of 2,427 billion cubic feet of gas (BCFG) and 9.81 million barrels of natural gas liquids (MMBNGL). More than 87 percent of the gas (2,122 BCFG) is estimated to be within the hypothetical Columbia Basin Continuous Gas AU, which encompasses an area of more than 4 million acres. A mean of about 30 BCF of conventional gas is estimated in the hypothetical Eastern Oregon and Washington Conventional Gas AU 503.

Introduction

As part of the U.S. Geological Survey's (USGS) effort to assess the potential for undiscovered petroleum accumulations throughout the United States, an assessment was conducted in 2006 to estimate the undiscovered gas resources of the Eastern Oregon and Washington Province (fig. 1) (Brownfield and others, 2006). This report provides additional geologic detail concerning the total petroleum system and assessment units that were defined, as well as a more detailed rationale for the quantitative assessment input. At present, there is no oil and gas production in eastern Oregon and Washington.

The Eastern Oregon and Washington Province (Province 5) is bounded on the west by the crest of the Cascade Range, on the north by the International Boundary, on the east by the

Figure 1. Area of Eastern Oregon and Washington Province in north-central and northeastern Oregon and eastern Washington and location of the Rattlesnake Hills gas field. Province boundary shown in red.

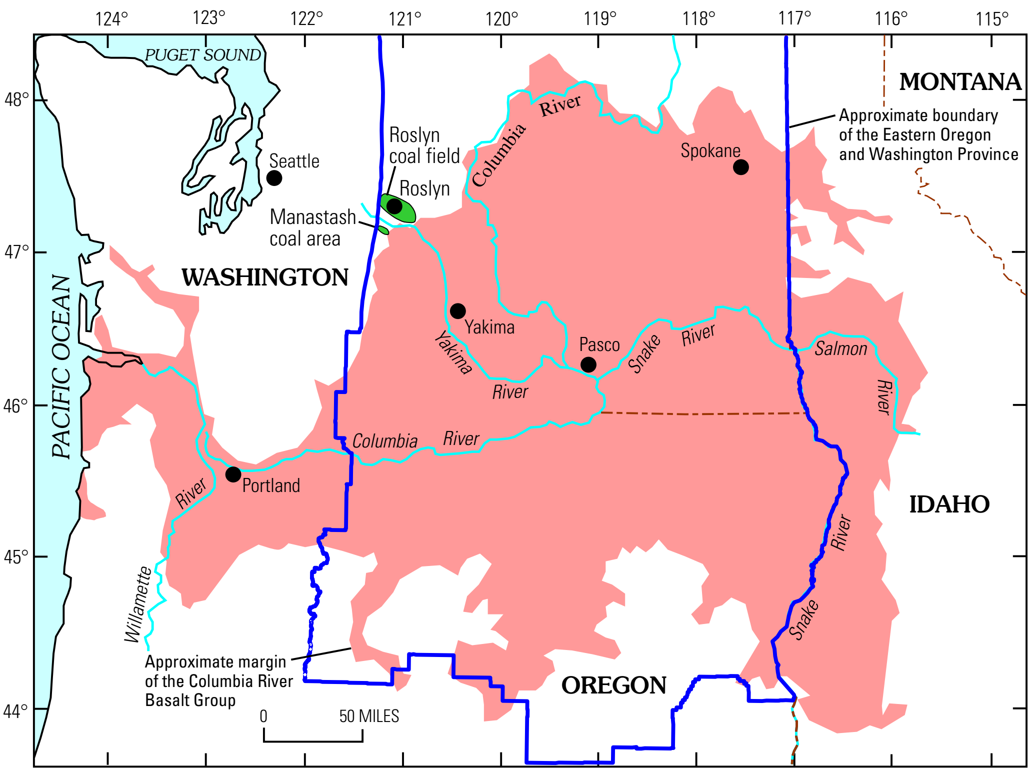

Figure 2. Approximate extent of the Columbia River Basalt Group (red shading) in Idaho, Oregon, and Washington, the approximate boundary of the Eastern Oregon and Washington Province, and the approximate location of the Roslyn coal field. The Columbia River Basalt Group is a series of Miocene basalt flows and volcaniclastic rocks more than 15,000 ft thick (Berkman and others, 1987). Modified from Reidel, Fecht, and others (1989).

Figure 3. Columbia River Basalt Group exposures along the Columbia River; view is north from Oregon side of the river. The town of Lyle, Wash., is visible on left side of photograph.

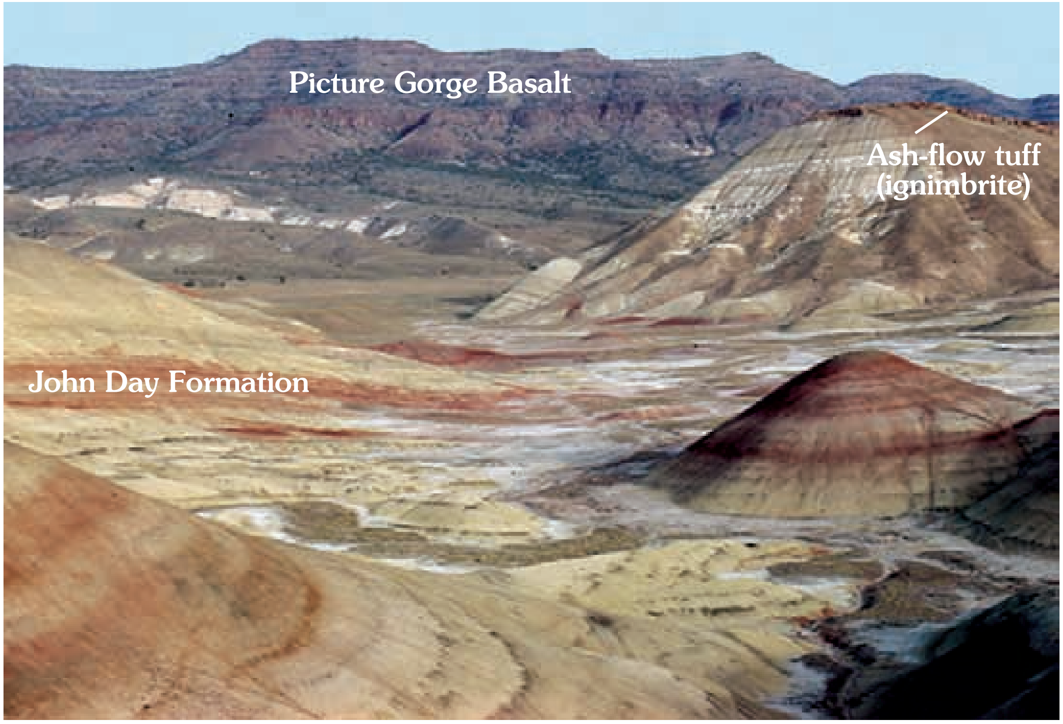

Figure 4. Tertiary volcanic and volcaniclastic rocks in the Painted Hills Unit of the John Day Fossil Beds National Monument, north-central Oregon. Exposures of the Oligocene John Day Formation are in lower and middle parts of view, and those of the Miocene Columbia River Basalt Group in the background. The regionally extensive ignimbrite divides the John Day Formation into two units.

Idaho State line, and on the south by a series of Oregon county lines that generally separates central Oregon from the northern part of the western Great Basin Province. The province is about 300 mi long and 200 mi wide, covering about 60,000 mi^2 in eastern Oregon and Washington (fig. 1).

The only hydrocarbon production within the province was from the now-abandoned Rattlesnake Hills gas field (Hammer, 1934) in south-central Washington (fig. 1) that was discovered in 1913 during the drilling of a water well in the Columbia River Basalt Group. The field was developed in 1930 and produced an estimated 1.3 billion cubic feet (BCF) of gas (McFarland, 1979) from vesicular basalt reservoirs before abandonment in 1941.

Much of the central part of the Eastern Oregon and Washington Province is overlain by the Miocene Columbia River Basalt Group (CRBG, figs. 2 and 3), which ranges in thickness from 4,000 ft to 13,800 ft in the Pasco, Wash. area (Reidel, Fecht, and others, 1989). Magnetotelluric survey data (Berkman and others, 1987) indicates that the CRBG possibly thickens to more than 15,000 ft northwest and west of Pasco. The southernmost part of the province is overlain by Miocene to Quaternary volcanic rocks (fig. 4).

Several hydrocarbon exploration holes drilled in the north-central part of the province confirmed the presence of at least 5,000 to more than 10,000 ft of Paleogene nonmarine arkose, mudstone, coal and volcanic rocks below the Columbia River Basalt Group (Campbell and Banning, 1985; Campbell, 1989) in central Washington (fig. 5). Gas shows were present in some of the wells, and drill-stem tests confirmed the presence of gas (Wilson and others, this volume), but the wells were abandoned as noncommercial. The first new drilling since 1989 was initiated by EnCana Corporation (Montgomery, 2008) with the drilling of the Anderville Farms 1-6 well (planned depth approximately 14,000 ft) about 7 mi northeast of Yakima, Wash. (fig. 1), Drilling began in January 2005 and was completed in early 2007. EnCana completed two other wells by the end of 2007, the EnCana Anderson #11-5 and the EnCana Brown #7-24 located in Yakima County, Wash.; this is interpreted to represent an industry commitment to continue and actively explore for gas in the Pacific Northwest.

A thick succession of Paleocene to Eocene fluvial arkosic sandstones and interbedded mudstones and coals is widespread within disconnected sub-basalt basins throughout the Eastern Oregon and Washington Province (Frizzell, 1979; Walker, 1980; Tabor, Waitt, and others, 1982, Tabor, Zartman, and Frizzell, 1984; Johnson, 1984a; Tennyson and Parrish, 1987; Tennyson, 1995). The units include the Swauk, Manashtash, Chumstick, and Roslyn Formations (fig. 5). In central Washington, for example, Eocene nonmarine arkosic sedimentary rocks of the Chuckanut Formation may exceed 20,000 ft in thickness in the northwest-trending Chiwaukum graben (fig. 6; Gresens and others, 1981; Evans, 1991). Campbell (1989) constructed an isopach map that indicates the lower and middle Tertiary section may be as much as 23,000 ft thick near Yakima, Washington (fig. 6).

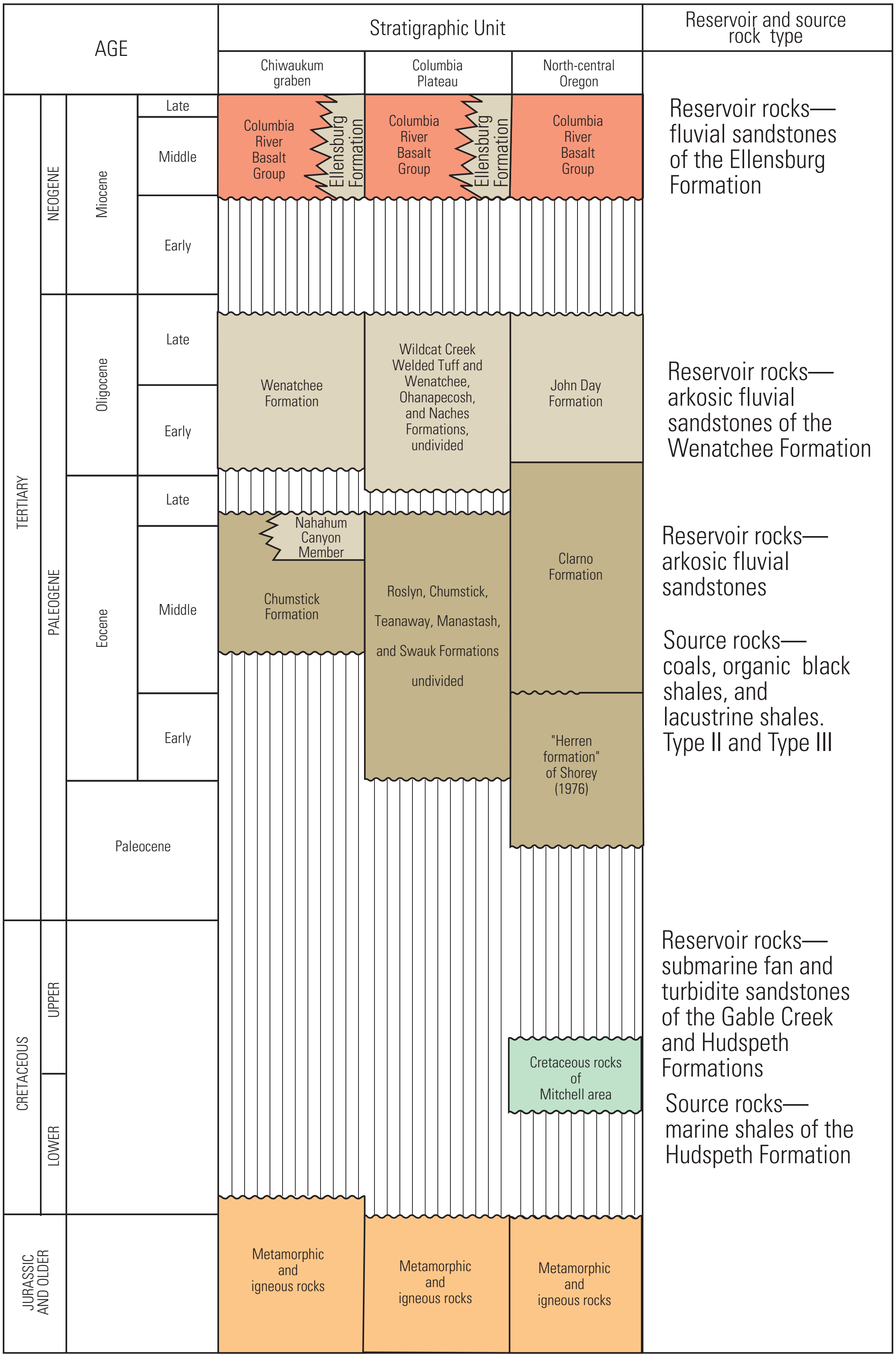

Figure 5. Stratigraphic columns for the Chiwaukum graben, Columbia Plateau, and north-central Oregon showing age, formation, and reservoir and source rock types in the Eastern Oregon and Washington Province.

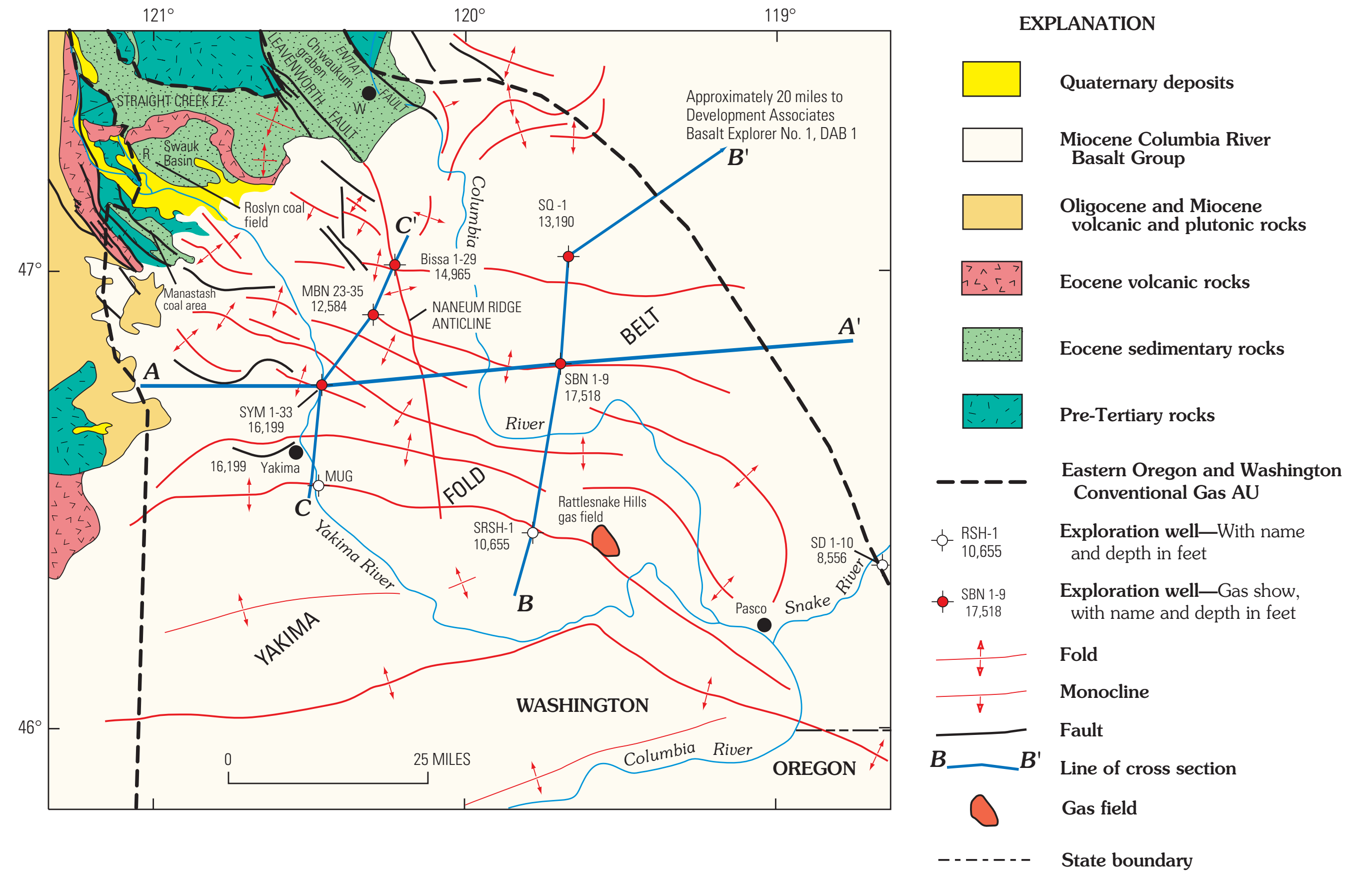

Figure 6. Generalized geology of northern part of the Eastern Oregon and Washington Conventional Gas Assessment Unit in central Washington, showing geologic units, cross section lines (*A-A'*, fig. 7; *B-B'*, fig. 31; *C-C'*, fig. 32), exploration wells, faults, fold axes, Roslyn coal field, and the Manastash coal area, central Washington. The Yakima fold belt is generally located north and west of the Yakima River within Columbia River Basalt Group. Modified from Johnson and others (1993) and Campbell (1989). SD 1-10, Shell Darcell No. 1-10; DAB 1, Development Associates Basalt Explorer No. 1; FZ, Fault zone; R, Roslyn; SQ 1, Shell Quincy No. 1; SBN 1-9, Shell Burlington Northern 1-9; SRSH-1, Standard Oil Rattlesnake Hills No. 1; MUG, Miocene Petroleum Company Union Gap; SYM 1-33, Shell Yakima Minerals Company 1-33; MBN 23-35, Meridian Burlington Northern 23-35; Bissa 1-29, Shell Bissa 1-29; W, Wenatchee.

The assessment of the Eastern Oregon and Washington Province was geology-based and applied the total petroleum system (TSP) concept. The geologic elements of a TPS include hydrocarbon source rocks (source rock maturation and hydrocarbon generation and migration), reservoir rocks (quality and distribution), and traps for hydrocarbon accumulation. Using these geologic criteria, the USGS defined the Cretaceous-Tertiary Composite Total Petroleum System, and three assessment units (AU) within it: the Eastern Oregon and Washington Conventional Gas AU, the Columbia Basin Continuous Gas AU, and the Republic Graben Gas AU. Undiscovered gas resources within the first two named AUs were quantitatively assessed; the Republic Graben Gas AU was not assessed.

Eastern Oregon and Washington Province Geology

The Eastern Oregon and Washington Province is located within a complex geologic setting east of the western continental margin of North America. Much of the province is overlain by the Miocene Columbia River Basalt Group (figs. 1, 2, 3), which is as much as 13,800 ft thick in the Pasco, Wash. area (Reidel, Fecht, and others, 1989; Reidel, Tolan, and others, 1989). In addition, the southernmost part is overlain by Miocene to Quaternary volcanic and volcaniclastic rocks (fig. 4), so direct knowledge of the underlying stratigraphy and structural geology is limited across much of the province.

Much of the province is most likely underlain by pre-Tertiary metamorphic, igneous, and sedimentary rock complexes that form several separate accreted crustal terranes that generally have allochthonous and (or) arc origins during Paleozoic and Mesozoic time (Whetten and others, 1980; Frizzell and others, 1982; Tabor, Zartman, and Frizzell, 1982; Johnson, 1985; Tennyson and Parrish, 1987; Tennyson, 1995). These rocks crop out along the north, east, and south margins of the CRBG, and most likely underlie much of the central and northern parts of the province. By the early Eocene, the pre-Tertiary rocks had formed the framework of the Washington continental margin (Johnson, 1985). The Eocene continental margin was cut by a major Late Cretaceous-early Tertiary dextral transcurrent fault system that includes the Straight Creek, Leavenworth, and Entiat Faults (fig. 6, Gresens, 1982; Johnson, 1984b, 1985); these features form the Chiwaukum graben and the Swauk Basin, the southern extensions of which are unknown because of burial by the Miocene Columbia River Basalt Group. In the northern part of the province, the source areas for the Paleogene sedimentary rocks are presumed to be the Northern Cascades and Okanogan uplands of northeastern Washington (Gresens and others, 1981; Johnson, 1984a; Heller and others, 1987). The Idaho batholith was emplaced in the Cretaceous and unroofed by early Challis time (Paleocene); it might be one of the sources of the nonmarine arkose and coal-bearing Paleogene rocks in the Oregon part of the province (Heller and Dickinson, 1985; Heller and others, 1985, 1987).

Central Washington

Early Tertiary uplift and extension (Johnson, 1985) produced subsidence and fault-bounded grabens and half-grabens that were rapidly filled with fluvial, lacustrine, and volcanic rocks of Paleogene age (Frizzell, 1979; Walker, 1980; Tabor, Waitt, and others, 1982; Tabor and others, 1984; Johnson, 1984a; Tennyson and Parrish, 1987; Tennyson, 1995). The units include Eocene Swauk Formation, Manastash Formation (coal-bearing), Teanaway Formation, Chumstick Formation, and Roslyn Formation (coal-bearing) (fig. 5), which are, in turn, overlain unconformably by the Oligocene Wenatchee and Ohanapecosh Formations. A west to east cross section was constructed north of Yakima (figs. 6, 7), showing formations, hypothetical faults, and exploration holes, and depicting the Columbia Basin in central Washington as an interpreted rift-graben structure.

At least 5,000 ft to possibly more than 10,000 ft of nonmarine Eocene to Oligocene arkose, mudstone, coal, and volcanic rocks are present below the Columbia River Basalt Group (CRBG) in central Washington (figs. 5, 7). The two wells shown in figure 6 and in the hypothetical cross section (fig. 7) are the Shell Yakima Minerals 1-33 well (fig. 6), which penetrated about 10,400 ft of Paleogene rocks below the CRBG and the Shell Burlington Northern1-9 well (fig. 6), which penetrated a Paleogene section about 5,000 ft thick (Campbell and Banning, 1985; Wilson and others, 2007). Two other deep exploration wells (fig. 6) tested the Paleogene

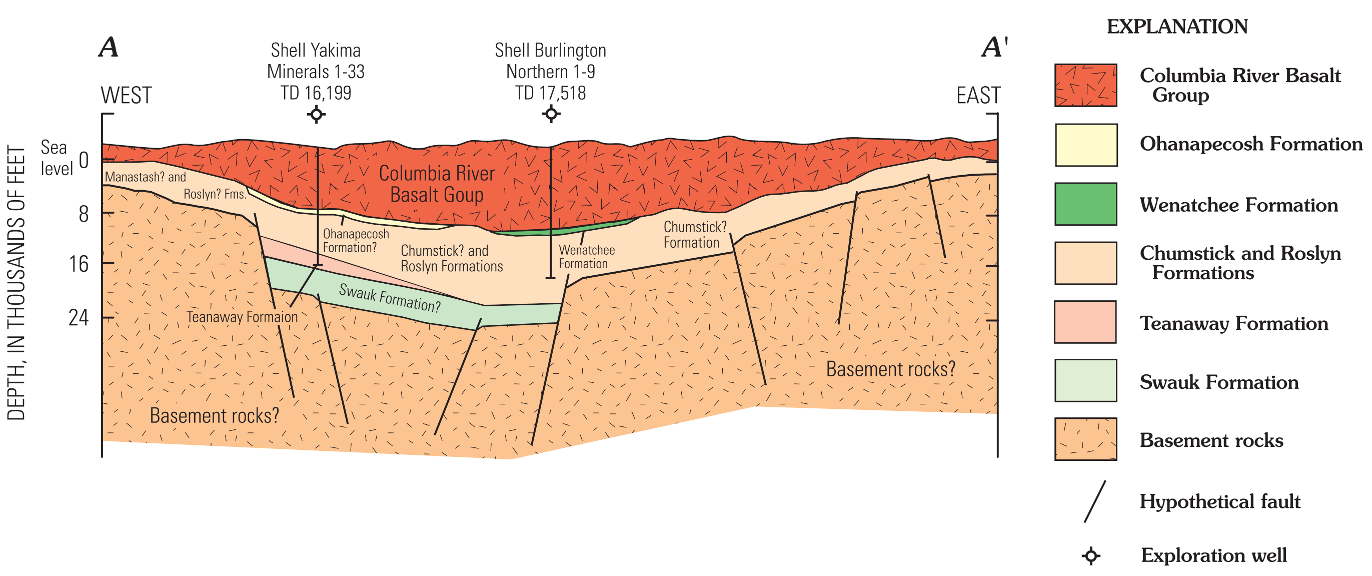

Figure 7. Interpretive west to east cross section portraying the Columbia Basin in central Washington as a rift-graben structure, with faulted pre-Tertiary basement rocks overlain by Paleocene to Oligocene, largely sedimentary strata, and by the Miocene Columbia River Basalt Group. Not to scale. See map, figure 6, for location of cross section. The Shell Yakima Minerals Company 1-33 well penetrated a Paleogene section about 10,400 ft thick, whereas the Shell Burlington Northern 1-9 well penetrated a section about 5,000 ft thick (Campbell and Banning, 1985; Wilson and others, this volume). Stratigraphic well-picks modified from Campbell and Banning (1985), Tennyson and Parrish (1987), Campbell (1989), and Wilson and others (this volume). Cross section modified from Wilson and others (this volume).

section: (1) The Shell Bissa 1-29, which penetrated more than 10,300 ft of Eocene to Oligocene rocks; and (2) the Shell Quincy No. 1 well, which penetrated about 5,590 ft of Eocene rocks. Thick sections of Eocene rocks crop out around the margins of CRBG exposed areas in the northwestern part of the province and consist of fluvial arkosic sandstone and interbedded mudstone and coal (Gresens and others, 1981; Evans, 1991).

The lower to middle Eocene Swauk Formation (Tabor and others, 1984; Taylor and others, 1988; Tabor and others, 1993; Tabor and others, 2000) consists of some 25,000 ft of nonmarine arkosic sandstone, siltstone, lacustrine shale, and carbonaceous shale and siltstone. The Swauk Formation was deposited in alluvial fans and in braided and meandering fluvial and lacustrine environments. Medium- to coarse-grained arkosic sandstones are common in the Swauk, which also includes andesitic to rhyolitic volcaniclastic rocks of the Silver Pass Member (Tabor and others, 1984). The Silver Pass Member is locally as much as 5,900 ft thick, and Tabor and others (1984) reported that about 15,750 ft of Swauk strata is present below it and possibly another several thousand feet of section overlying the Silver Pass. Taylor and others (1988), for example, measured more than 10,500 ft of section above the Silver Pass Member. Tabor and others (2000) indicated that the Swauk Formation may be as much as 26,250 ft thick, and Johnson (1985, table 1, p. 291) reported a thickness of about 25,400 ft. Frizzell (1979) estimated that a minimum of 7,500 ft of section is present between the base of the Swauk Formation and the overlying Teanaway Formation just northeast of the Roslyn coal field (fig. 2). Tabor and others (1984) suggested that the Upper Cretaceous Mount Stuart batholith was the major sediment source and that the drainage was to the south. Paleocurrent data collected from the eastern part of the Swauk Basin (Johnson, 1985), as well as the presence of an eastern-derived conglomerate (Tabor and others, 1993), indicate that eastern sources were also important. In the eastern part of the basin, the upper part of the Swauk section consists of 1,180 ft of lacustrine strata with eastward-trending paleocurrents that were interpreted as evidence for some local internal drainage conditions (Taylor and others, 1984). The Swauk Formation contains potential hydrocarbon source rocks with Type III kerogen; total organic carbon (TOC) content ranges from 0.03 to 1.1 weight percent (Lingley and Walsh, 1986; Tennyson and Parrish, 1987; Walsh and Lingley, 1991; Tennyson, 1995). Sandstone porosity values from deep well samples range from 4.9 to 7.9 percent (Lingley and Walsh, 1986; Walsh and Lingley, 1991; Myer, 2005).

The Swauk Formation is unconformably overlain by the Eocene Teanaway Formation, (Frizzell, 1979; Walker, 1980; Tabor and others, 1983; Tabor and others, 1984). Within the province area, the Teanaway Formation consists of basaltic pyroclastic tuffs and breccia and basalt flows, dikes, and sills; it ranges in thickness from 30 ft to 8,200 ft. This extreme range in thickness is a function of the distance from the Teanaway volcanic centers (Tabor and others, 1984). About 20 percent of the formation contains arkosic sandstone, fresh-water limestone, and carbonaceous shales (Walker, 1980). One carbonaceous shale zone northeast of the Roslyn coal field (fig. 2) was described by Walker (1980) as a 20-ft-thick “dirty” coal.

South of the Yakima River, near Roslyn, Wash. (fig. 2), the lower Eocene Manastash Formation unconformably overlies pre-Tertiary rocks in the Manastash coal area, as can be observed in several outcrops. The formation (fig. 5) was named by Smith (1904, p. 7) for the sandstone and finer-grained sedimentary rocks, exposed in the upper reaches of Manastash and Taneum Creeks south of Roslyn, Washington (figs. 1, 2, Tabor, Waitt, and others, 1982, 1984; M.E. Brownfield and R.H. Affolter, written commun., 1996). It is a nonmarine succession of fine- to medium-grained arkosic sandstones, siltstones, shales, carbonaceous shales, and coal totaling about 3,100 ft thick. Lewellen and others (1983) gave a minimum thickness of 3,200 ft. Coal beds within the Manastash coal area (figs. 2, 6) range in thickness from less than 1 ft to as much as 14 ft (Saunders, 1914; Lewellen and others, 1985; M.E. Brownfield and R.H. Affolter, written commun., 1996); they are bituminous in rank, with ash yields ranging from 4.2 to more than 25 weight percent and sulfur contents from 0.3 to 1.1 weight percent. The thicker coal beds contain several coal benches with thin carbonaceous partings. Thin beds of white to gray claystone in the carbonaceous shale and coal zones represent altered volcanic ash. Newman (1977) suggested that the Manastash Formation is equivalent to the Swauk Formation based on preliminary palynomorph data (fig. 5; also, see Johnson, 1985). As such, it may either be a downslope equivalent of the Swauk or it may have been deposited in a small graben associated with the Straight Creek fault zone, as was interpreted by Tabor and others (1984), who reported a thickness of 2,500 ft. The Manastash Formation is overlain unconformably by basalts of the Miocene Columbia River Basalt Group.

Above the Teanaway Formation, and probably conformable with it, is the coal-bearing Roslyn Formation (Bressler, 1951; Frizzell, 1979; Walker, 1980; Tabor and others, 1984; Tabor and others, 2000). The Roslyn was first described by Russell (1900) without designating a type section, and Bressler (1951) divided it into lower, middle, and upper members based on variations in grain size and the presence of coal. Deposition was in a fluvial environment. The formation consists of mostly white thick-bedded feldspathic sandstone with minor conglomerate, carbonaceous shale, and coal; its total thickness is about 8,500 ft (Walker, 1980; Tabor and others, 2000). The lower member is about 3,000 ft thick and crops out mostly north of the Teanaway River (Walker, 1980), just north of Roslyn coal field (figs. 2, 6). The lower half of this member contains interbedded rhyolite flows and tuffs, tuffaceous to arkosic sandstones, conglomerate, siltstone, claystone, and carbonaceous shale. The upper half is somewhat finer grained and has fewer conglomeratic sandstones and no rhyolite or carbonaceous shale interbeds.

The middle member of the Roslyn Formation was defined by Bressler (1951) on the basis of overall, finer grained sandstone beds and the presence of coal and carbonaceous shale. It is about 3,000 ft thick northeast of Roslyn (figs. 2, 6) and appears to thin toward the northwest (Walker, 1980). The member consists mostly of medium-grained, commonly poorly indurated sandstone, with minor pebbly sandstone, siltstone, shale, carbonaceous shale, and coal. Coal beds increase in number and thickness upward.

The base of the upper member of the Roslyn Formation has been defined as the base of the No. 8 or Wright coal bed. Bressler (1951) stated that the member is about 1,500 ft thick, with eight important coal beds. Walker (1980), however, believed it to be about 2,400 ft thick and to contain an additional 16 coal beds. The unit consists of mostly medium grained sandstone with siltstone, shale, carbonaceous shale, and coal. The coal beds in the Roslyn field are mostly high volatile A bituminous in rank, except for the Roslyn bed, which is high-volatile B bituminous rank (Beikman and others, 1961); these rank assignments indicate vitrinite reflectance (R_o) values ranging from 0.7 percent to 1.0 percent (Stach and others, 1982, table 4, p. 45). The coals have ash yields ranging from 12 to 17.6 weight percent and contain 0.3 to 0.5 weight percent sulfur. Many of the additional 16 coal beds described by Walker (1980) are mostly carbonaceous shale with thin coal benches. Total thickness of the entire Roslyn Formation is about 8,500 ft; age probably ranges from middle to late Eocene (Frizzell, 1979; Tabor and others, 2000). Palynomorph data reported by Newman (1975) indicates that the upper part of the Roslyn Formation probably correlates with the coal-bearing part of the Puget Group (Vine, 1969) of middle to late Eocene age, east of Seattle, Wash. (fig. 1). The source of the nonmarine sediments was to the northeast and east. Sandstone porosity values from deep drill holes range from 3.9 to 22.1 percent (Lingley and Walsh, 1986; Walsh and Lingley, 1991; Myer, 2005; Wilson and others, this volume).

The middle to upper Eocene Chumstick Formation (Whetten, 1976; Frizzell, 1979; Gresens and others, 1981; Evans, 1987; Evens, 1991; Evans, 1994) is a thick succession of fluvial and lacustrine rocks that crops out in the Chiwaukum graben (fig. 6), which is also known as the Chumstick Basin. Within the graben, the total thickness might be as much as 29,860 ft (Chappell, 1936; Gresens, 1983; Johnson, 1985), but its true thickness is uncertain; Chappell (1936), for example, considered that thickness to be unreliable and concluded that it resulted from undetected isoclinal folding. However, Gresens (1983) stated that there are no overturned beds and that the well-documented tuff stratigraphy indicates a continuous section. Gresens and others (1981) and Whetten (1976) estimated the thickness of the Chumstick to be about 19,000 ft.

The Chumstick Formation consists of medium- to coarse-grained arkosic sandstone with greenish to bluish shale, conglomerate, and siliceous tuff. The Chumstick was deposited in alluvial-fan, fluvial, and lacustrine environments during humid-tropical paleoclimate conditions (Evans, 1991; Tabor, Waitt, and others, 1982). The organic matter is mostly Type III kerogen, and total organic carbon (TOC) ranges from 0.13 to 5.97 weight percent (Tennyson and Parrish, 1987). The Nahahum Canyon Member in the upper part of the Chumstick Formation is about 6,200 ft thick (Evans, 1994, 2000) and consists of sandstone and shale with organic matter. It was deposited in fluvial and shallow lake-deltaic environments (Gresens and others, 1981). The lacustrine-deltaic deposits contain 3 to 5 weight percent of TOC (Evans, 2000). Sedimentary structures indicate that transport direction was mostly to the southwest (Buza, 1979), but the matrix mineral suite in the conglomerates indicates a probable west to southwest source (Frizzell and Tabor, 1977; Tabor, Waitt, and others, 1982). Thin tuff beds occur throughout the Chumstick Formation and have been traced for several miles (Tabor, Waitt, and others, 1982). Fission-track ages on zircons indicate that deposition of the tuffs took place about 45 Ma, and at a rapid rate. The 45 Ma age is similar to that of plutons northeast of the Chumstick graben, indicating a possible source to the north (Tabor, Waitt, and others, 1982), but Johnson (1984b) suggested that the main source resulted from rapid uplift of crystalline terranes to the east.

South of the Manastash coal area and northwest of Yakima (fig. 6) is a complexly deformed nonmarine section that unconformably overlies the pre-Tertiary basement and belongs to the middle to upper Eocene and Oligocene? Naches Formation (fig. 5; Tabor and others, 1984, 2000). This formation is mostly a succession of rhyolitic to basaltic volcanic rocks with nonmarine fine- to medium-arkosic sandstones, siltstones, shales, carbonaceous shales, and thin coals (Lewellen and others, 1985; Walsh and others, 1987; Tabor and others, 2000). Basalt and rhyolite flows, tuffs, and breccias are interbedded with the arkosic strata. The Naches Formation ranges in thickness from 4,900 to 9,800 ft (Tabor and others, 2000). Thin porcelanite beds associated with coals and carbonaceous shales (M.E. Brownfield and R.H. Affolter, written commun., 1996) consist of altered volcanic ash (tonsteins) that have been thermally altered, which indicates that the Naches Formation is possibly thermally mature resulting from contemporaneous volcanic activity or burial by younger rocks. Coal beds are less than 1 ft in thickness, and discontinuous. The formation may correlate with the Roslyn Formation and is unconformably overlain by the Ohanapecosh Formation and the Columbia River Basalt Group (Tabor and others, 2000).

The late Eocene? to Oligocene Ohanapecosh Formation crops out in the west-central part of the Eastern Oregon and Washington Province (Fiske and others, 1963; Tabor and others, 2000) and is the oldest unit associated with the Cascade Range (fig. 5). First use of the name Ohanapecosh Formation is credited to Fiske and others (1963), who considered the unit to be middle Eocene to early Oligocene. The Ohanapecosh Formation contains thick lenticular flows of basalt and andesite, andesitic to dacitic tuffs, and breccia (Vance and others, 1987) and water-laid volcaniclastic rocks (mudflows), which are mainly massive tuff-breccias interstratified with thin-bedded volcanic siltstones, volcanic graywackes, and gritty pumice conglomerates; thickness exceeds 10,000 ft. Rocks assigned to the Ohanapecosh Formation underlie most of the southern part of the Washington Cascades (Walsh and others, 1987; Smith, 1993). The eruption and deposition of these rocks marked the end of Eocene strike-slip faulting and magmatism (Tabor and others, 1984; Johnson, 1985) in Washington and the initiation of the Cascade Arc (Vance, 1982; Frizzell and Vance, 1983). Sandstone porosity values from deep drill holes range from 9.0 to 17 percent (Lingley and Walsh, 1986; Walsh and Lingley, 1991; Myer, 2005). Wilson and others (this volume) reported porosity values ranging from 10 to 20 percent for the Wildcat Creek facies (Campbell, 1989), which may be age equivalent to the Ohanapecosh Formation.

The Oligocene Wenatchee Formation (Gresens, 1976; Gresens and others, 1977; Frizzell, 1979; Tabor, Waitt, and others, 1982) unconformably overlies the Roslyn and Chumstick and is unconformably overlain by the Columbia River Basalt Group (fig. 5). The Wenatchee is generally separated from the underlying Chumstick Formation by its gentle dips, quartz-rich composition, and variegated shales (Frizzell, 1979; Tabor, Waitt, and others, 1982). The lower half of the formation contains mostly bluish-gray, micaceous, tuffaceous shale and siltstone with interbedded quartz sandstone (Tabor, Waitt, and others, 1982). The upper part contains crossbedded quartz sandstone beds as much as 45 ft thick overlain by shale and sandstone, with the uppermost part consisting of conglomerate with felsic volcanic clasts. Palynomorph data reported by Newman (1975) indicate an Oligocene age for the Wenatchee Formation, which is supported by fission track ages (Gresens and others, 1977). Campbell (1989) and Myer (2005) reported thicknesses ranging from 900 to 1,000 ft, and Frizzell (1979) reported a thickness of more than 1,180 ft at the type locality. The Wenatchee Formation was deposited in a fluvial environment (Myer, 2005). Porosity data from sandstone units penetrated by drilling have been reported to range from 6 to 20 percent (Lingley and Walsh, 1986; Walsh and Lingley, 1991: Myer, 2005; Wilson and others, this volume).

Unconformably overlying the Manastash, Roslyn, Naches, and Ohanapecosh Formations in the central part of the province (figs. 1, 6, 7) are basalts and minor volcaniclastics of the Columbia River Basalt Group (CRBG). The CRBG consists of more than 300 basalt flows that were erupted from fissures and vents in northeastern Oregon, easternmost Washington, and westernmost Idaho during the Miocene (Tolan and others, 1989). Individual basalt flows range in thickness from 10 to more than 300 ft and the total thickness is more than 13,800 ft (Reidel, Fecht, and others, 1989) in the Pasco, Wash. area (fig. 2). Magnetotelluric survey data (Berkman and others, 1987) indicate a thickening northwest of Pasco to possibly more than 15,000 ft (Reidel, Fecht, and others, 1989) within the Yakima fold belt (fig. 6). The fold belt is generally north and west of the Yakima River within the CRBG. The fold belt is characterized by CRBG flows and sedimentary units that have been folded under north to south compression (Reidel, Fecht, and others, 1989), forming a series of contemporaneous anticlinal ridges and synclinal valleys trending east-west to southeast-northwest that resulted in thickening of the sequence within the north-central part of the province. The CRBG has been divided into six formations (fig. 8) by Swanson and others (1979); isotopic ages of individual flow units are shown in figure 8. Some of the flows cover thousands of square miles, and at least 20 flows have traveled hundreds of miles along the ancestral Columbia River to the Willamette River Valley (Tolan and others, 1989), continuing to the Pacific coast (fig. 2) from their source. The group has a volume of about 174,000 km^3 and covers about 164,000 km^2 (Tolan and others, 1989). The Grande Ronde Basalt is the most voluminous and areally extensive unit, with an estimated volume of about 150,000 km^3 (Swanson and Wright, 1981; Reidel, Fecht, and others, 1989).

The Miocene Ellensburg Formation is interbedded with the Grande Ronde, Saddle Mountains, and Wanapum Basalts of the Columbia River Basalt Group (figs. 5, 7; Tabor, Waitt, and others, 1982, Tabor and others, 1984). The formation consists of conglomerates, lahars, lithic tuffaceous to arkosic sandstone, lacustrine shale, and carbonaceous shale.

Series		Group	Formation	Member	Isotopic age (Ma)
Miocene	Upper	Columbia River Basalt Group	Saddle Mountains Basalt	Lower Monumental Member	6
				Ice Harbor Member	8.5
				Buford Member	
	Middle			Elephant Mountain Member	10.5
				Pomona Member	12
				Esquatzel Member	
				Weissnefels Ridge Member	
				Asotin Member	13
				Wilber Creek Member	
				Umatilla Member	
			Wanapum Basalt	Priest Rapids Member	14.5
				Roza Member	
				Shumaker Creek Member	
				Frenchman Springs Member	
				Eckler Mountain Member	
	Lower		Grande Ronde Basalt (Prineville Basalt; Picture Gorge Basalt)		15.6
					16.5
			Imnaha Basalt		17.5

Figure 8. Stratigraphic column for the Miocene Columbia River Basalt Group showing formation and member names and geologic and isotopic ages. Modified from Swanson and others (1979) and Reidel and others (2002).

Sequences were derived from volcanoes in the ancestral Cascade Range to the west. Most of the sedimentary interbeds are only 15 to 25 ft thick, with thicker units locally 60 to 90 ft thick. Sedimentary structures indicate that the arkosic facies of the Ellensburg Formation was deposited on flood plains by small streams flowing southeastward (Tabor, Waitt, and others, 1982; Tabor and others, 1984) and was derived from the Swauk and Chumstick Formations and pre-Tertiary metamorphic rocks. Swamps and lakes were also present.

North-Central Oregon

Cretaceous marine and continental rocks crop out in north-central Oregon. Marine sandstone and mudstone and siltstone of the Albian to Cenomanian Hudspeth Formation lie unconformably on Permian metamorphic rocks (Wilkinson and Oles, 1968; Oles and Enlows, 1971) in north-central Oregon near the town of Mitchell (fig. 9). The Hudspeth Formation (figs. 10, 11) has been interpreted as marine mudstone and turbidites (Kleinhans and others, 1984; Dorsey and Lenegan, 2007). The formation (fig. 11) consists of olive-gray to dark-gray friable mudstones with interbedded siltstone, sandstone, and turbidites; it contains Type II and III organic matter (Sidle and Richers, 1985; Fisk and Fritts, 1987) ranging from 0.21 to 3.7 weight percent TOC. The basal part of the Hudspeth Formation consists, from oldest to youngest, of green sandstone, mudstone, conglomerate, and tan sandstone (Dorsey and Lenegan, 2007). The upper and main unit of the Hudspeth consists of thin-bedded turbidite sandstone and mudstone.

Sandstone and conglomerate units of the marine Gable Creek Formation intertongue with the Hudspeth (fig. 10). The Cenomanian Gable Creek (fig. 12) has been interpreted as submarine fan facies consisting of fan conglomerate and lithic

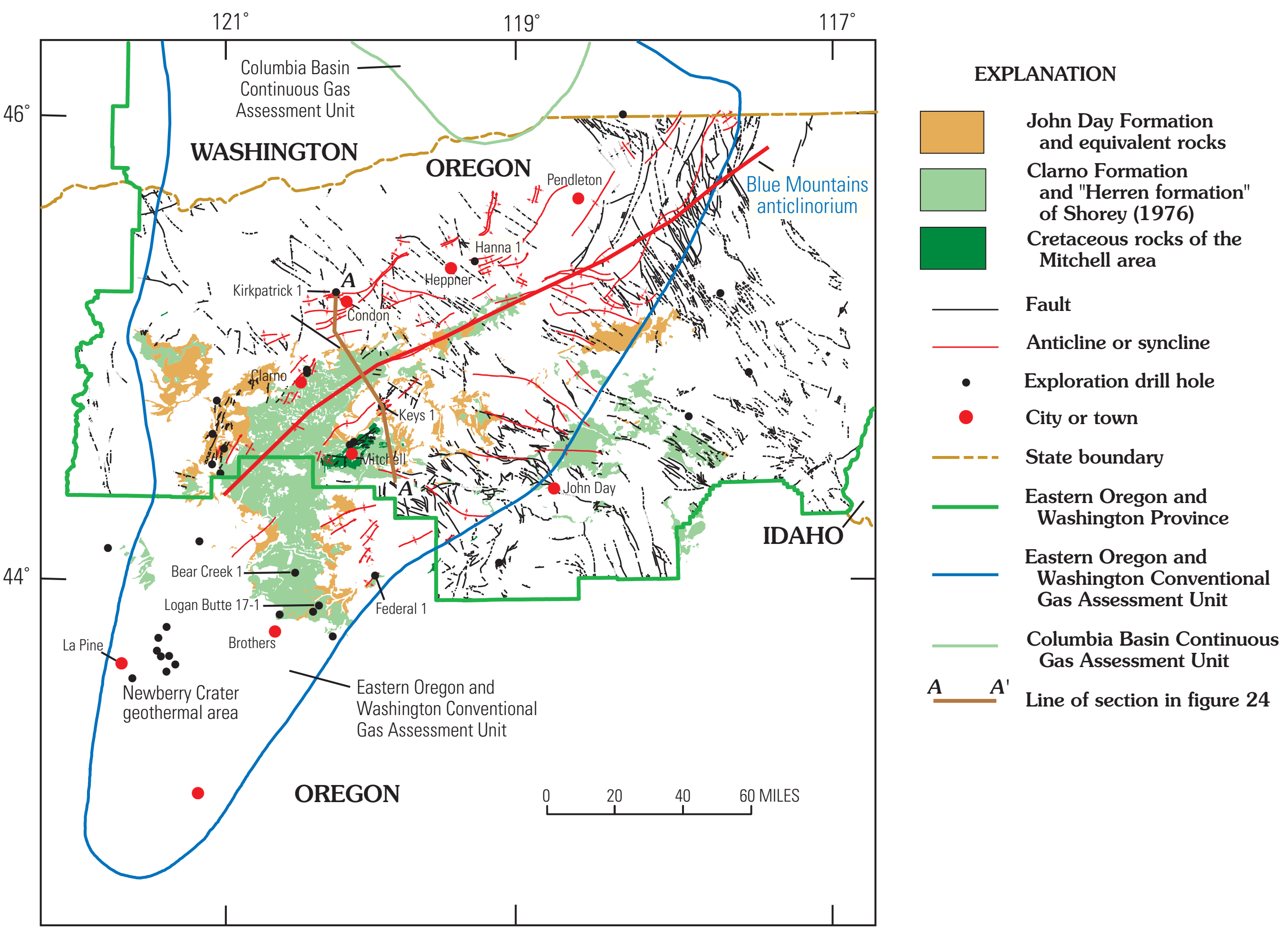

Figure 9. Generalized geology of the southern part of the Eastern Oregon and Washington Conventional Gas Assessment Unit (AU), in north-central Oregon, showing southern portion of the Eastern Oregon and Washington Province, assessment unit boundary, Blue Mountains anticlinorium, geologic units, faults, anticlines and synclines, exploration holes, and selected cities. Geologic units modified from Walker and others (2003). Much of the white area within the AU is Miocene and younger volcanic rocks. Line of section A-A' is for cross section in figure 24.

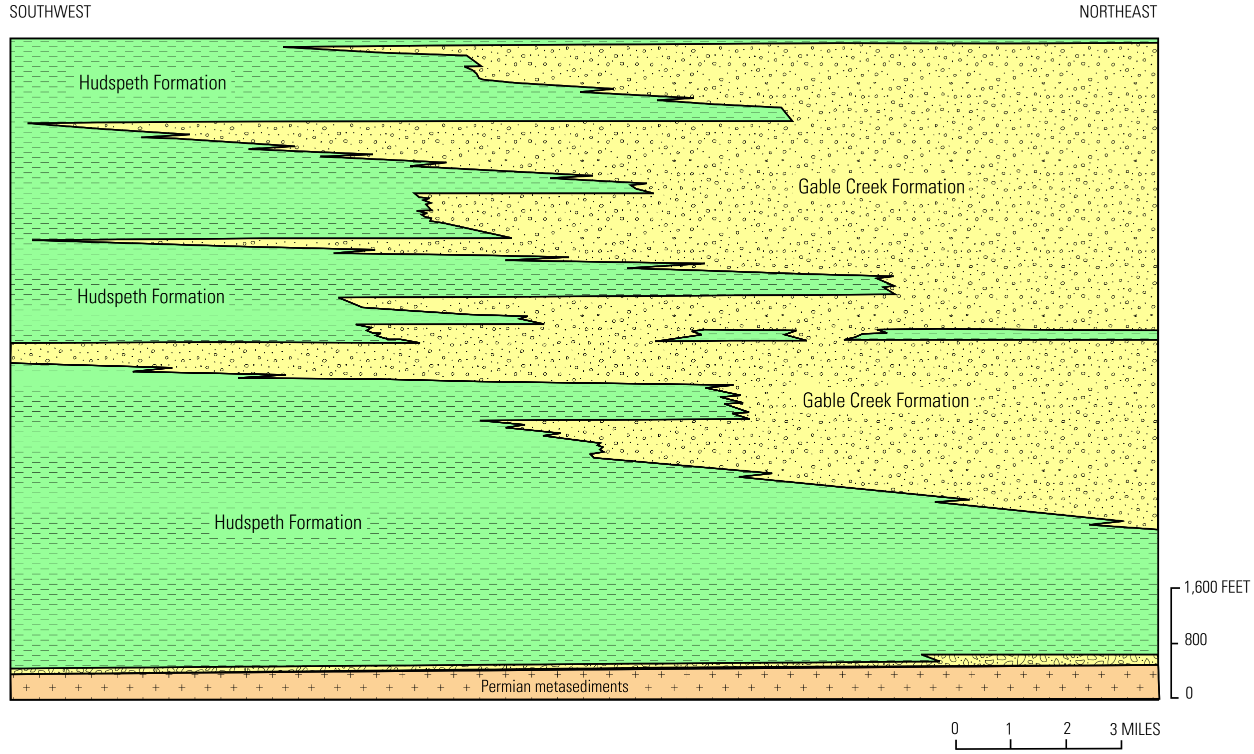

Figure 10. Schematic cross section showing intertonguing of marine turbidites of the Hudspeth Formation with submarine-fan facies of the Gable Creek Formation, Mitchell anticline, Mitchell, Oreg. Combined thickness of the two formations is at least 9,000 ft. Sediment transport was primarily from the south-southeast to the north-northwest (Sandefur and Fisk, 1989). Modified from Wilkinson and Oles (1968) and Oles and Enlows (1971).

Figure 11. Exposure of Upper Cretaceous Hudspeth Formation near Mitchell, Oreg., consisting of olive-gray to dark-gray friable mudstones with interbedded turbidite siltstone and sandstone. Sandstone and siltstone beds range from less than 1 to about 5 in. thick. Hudspeth Formation has been interpreted as a submarine fan and turbidite facies (Kleinhans and others, 1984). Bright green plant about 1.5 ft high.

arenite and turbidite sandstones and shales (Kleinhans and others, 1984); its basal contact with the Hudspeth Formation most likely is gradational. Conglomerate units near the base of the formation (fig. 13), near Mitchell, Oreg., contain chert, quartzite, and granite clasts with lesser amounts of quartz, phyllite, greenstone, mafic volcanic rocks, and sandstone (Oles and Enlows, 1971); matrix is mainly sandstone and cemented by calcite. Paleocurrent data indicate a sediment transport direction from the south-southeast to the north-northwest (Sandefur and Fisk, 1989).

A combined thickness of 9,000 ft for the Gable Creek and Hudspeth Formations was reported by Oles and Enlows (1971) and Fritts and Fisk (1985b), whereas Dorsey and Lenegan (2007) measured a combined thickness of about 7,220 ft northeast of Mitchell. About 2,000 ft of marine Jurassic to Cretaceous rocks, assumed to be Gable Creek and Hudspeth or equivalent, were penetrated in the Standard Kirkpatrick No. 1 well (Fox and Reidel, 1987a, 1987b) near Condon, Oreg. (fig. 9). This interval is overlain by about 4,555 ft of the upper Eocene to lower Oligocene Clarno? Formation and the Oligocene John Day Formation, in turn overlain by 2,440 ft of the Miocene Columbia River Basalt Group in the upper part of the well. The northern extent of the Cretaceous rocks is unknown, but Thompson and others (1984) reported fossil data indicating that exploration wells drilled southwest of Mitchell (fig. 9) reached Cretaceous marine rocks consisting mostly of mudstone deposited in neritic to bathyal depths. The Sunray Bear Creek 1 well (fig. 9) drilled through about 3,740 ft of probable Lower and Upper Cretaceous rocks and Texaco Logan Butte 17-1 well (fig. 9) penetrated about 4,270 ft of similar strata. The Federal 1 well (fig. 9) located east of these wells penetrated about 2,040 ft of Cretaceous rocks interpreted to be mostly nonmarine; the interval included a 180-ft thick middle marine section overlain by a 540-ft thick

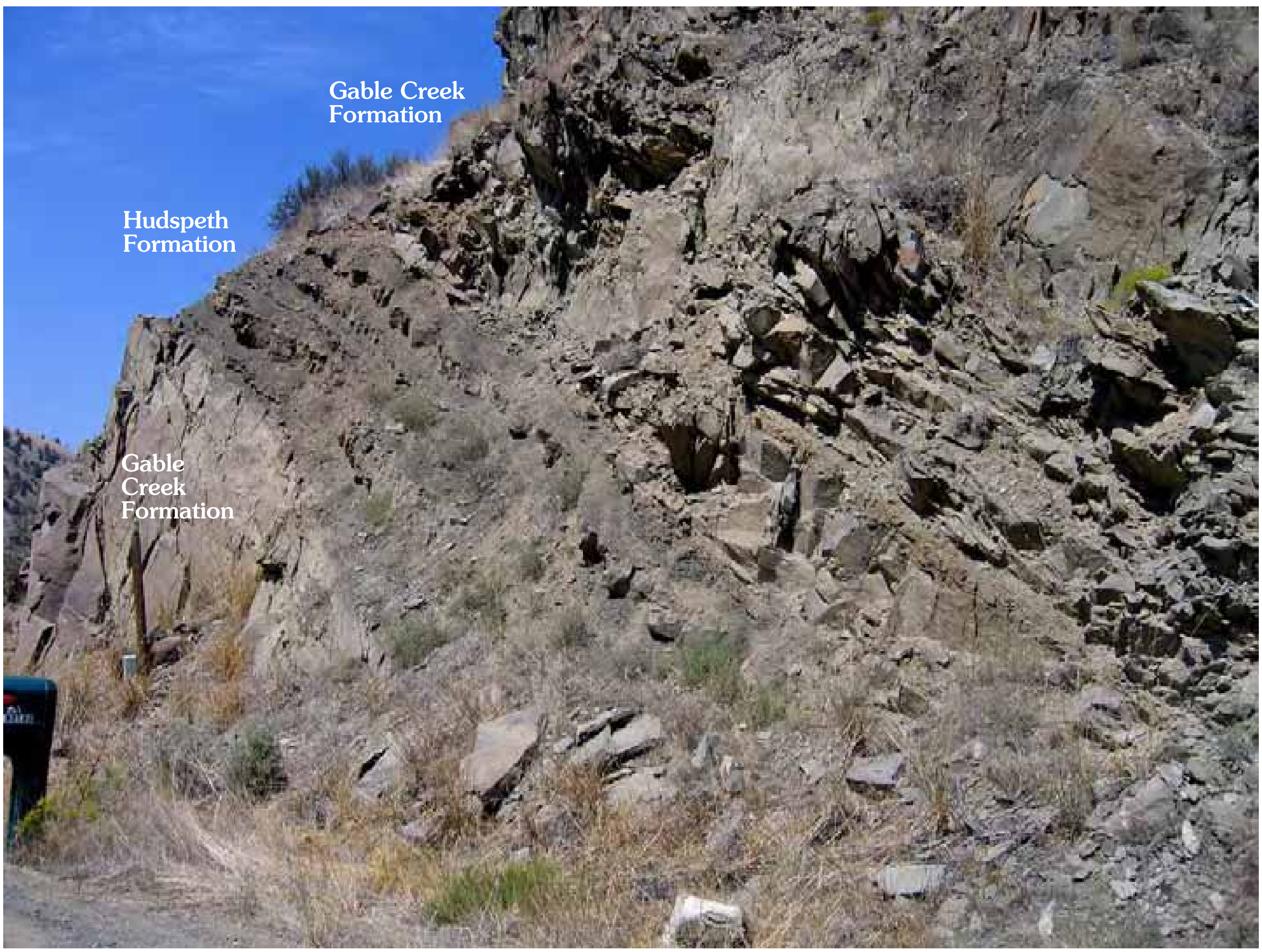

Figure 12. Exposure of interbedded strata of the Gable Creek Formation and Hudspeth Formation, near the town of Mitchell, Oreg. The Gable Creek Formation consists of interbedded submarine and turbidite conglomerate and lithic arenite and sandstone. The Hudspeth Formation consists of olive-gray to dark-gray friable mudstones with interbedded turbidite siltstone and sandstone. Mailbox at lower left is about 4 ft high.

Figure 13. Exposure of conglomerates near the base of the Gable Creek Formation, Mitchell, Oreg. Chert, quartzite, and granite are the most common clasts, with lesser amounts of quartz, phyllite, greenstone, mafic volcanic rocks, and sandstone. Matrix is sandstone cemented with calcite. Wallet is about 4.5 inches long.

section of nonmarine Maastrichtian to Paleocene rocks. The presence of thick Cretaceous sections in these wells and in the Mitchell area can be interpreted to indicate that an Albian-Cenomanian depositional basin existed in central Oregon and that Cretaceous strata are preserved below the Tertiary volcanic rocks (Thompson and others, 1984).

Outcrops of the Paleocene to lower Eocene “Herren formation” of Shorey (1976), exposing fluvial and deltaic arkosic sandstone with siltstone, shale, carbonaceous shale, and coal have been described along the flanks of the Blue Mountains anticlinorium (fig. 9). The thickest section follows the strike of the Blue Mountains anticlinorium (fig. 9), where it is about 2,000 ft thick. The upper parts of some sections of the “Herren formation” contain interbedded volcanic rocks (Pigg, 1961; Fritts and Fisk, 1985b; Ferns and Brooks, 1986). Coal beds from less than 1 ft to as much as 7 ft thick have been reported south of Heppner (fig. 8) but they are mostly bone or impure coal and carbonaceous shale (Mendenhall, 1907; Mason and Erwin, 1955; Ferns and Brooks, 1986). The arkosic sandstones have porosities ranging from 8 to 21 percent, with an average of 12 percent (Riddle and Fisk, 1987; Riddle, 1990) and permeabilities ranging from 0.4 to 73 mD (average 8 mD). Black shale and coal samples collected and analyzed from the “Herren formation” contain 0.04 to 23.9 weight percent TOC in the form of Type II and III kerogen (Fisk and Fritts, 1987), and a carbonaceous shale sample collected from a unit below the Clarno Formation in southern Morrow County (fig. 1) contains 4.72 weight percent TOC (Law and others, 1984).

The Clarno Formation (fig. 5) is generally widespread in north-central Oregon (fig. 9) and is overlain by John Day Formation and Columbia River Basalt Group (fig. 14). The Clarno Formation contains as much as 5,000 ft of mafic flows, volcanic breccias, mudflows, and volcaniclastics rocks, with associated nonmarine sedimentary rocks (Waters and others, 1951; Peck, 1964). The volcaniclastic units include coarse tuff, lapilli tuff, pyroclastic breccia, mudflows or lahars, and tuffaceous siltstone, sandstone, conglomerate, carbonaceous mudstone and shale, and thin coals. These rocks (fig. 15) represent subtropical alluvial fan, fluvial channel, mudflow, lacustrine, and volcanic airfall environments (Oles and Enlows, 1971; Beaulieu, 1972). Eocene fossil fruits and seeds (nuts), woods, leaves, flowers, and pollen collected from a prolific fossil site (fig. 15) include *Equisetum* (horsetails), palms, ferns, cycads, *Ginkgo* (maiden hair tree), magnolias, grapes, and a diversity of other plants, which support the interpretation of a subtropical to tropical environment (Manchester, 1981). The organic-rich lacustrine and fluvial rocks contain mostly Type III kerogen with TOC contents from 0.17 to 4.47 weight percent (Kuo, 1988). Subsurface samples yielded vitrinite reflectance values ranging from 0.33 to 0.85 (Kuo, 1988) from Steele Energy Keys 1-28 well.

The John Day Formation (fig. 5) unconformably overlies the Clarno Formation, the contact defined by a rhyolite ignimbrite that rests on a paleosol developed on andesite of the Clarno (Bestland and others, 1996; Smith and others, 1998). The John Day Formation (fig. 16) consists of at least 3,000 ft of rhyolite flows, air- and water-laid tuffs, ash-flow tuffs, and conglomerates (Beaulieu, 1972). Many of the tuffs are altered to zeolites (heulandite and clinoptilolite) and clays (fig. 17). Thinly bedded claystone units and thin lignites are evidence of lacustrine or mire deposition (Oles and Enlows, 1971). Most likely, the John Day strata are thermally immature except locally, where they may have been subjected to high heat flow during the Miocene. The John Day Formation is unconformably overlain by the Miocene Columbia River Basalt Group (figs. 5, 16).

The Cascade Range, extending from Canada to northern California, is an Andean-type volcanic arc that formed in the latest Eocene? or Oligocene time (Vance, 1982; Frizzell and Vance, 1983) and marked the end of Eocene strike-slip faulting and basin subsidence. Its formation diverted streams carrying eastern-derived arkosic sediments, thus reducing sedimentation rates from those eastern sources and providing a local source for volcanic-derived late Tertiary sedimentary rocks (Tabor and others, 1984; Johnson, 1985; Heller and others, 1987) in the Eastern Oregon and Washington Province. The rising Cascade Range separated many of the time-stratigraphic equivalent basins in both Oregon and Washington.

Cretaceous-Tertiary Composite Petroleum System (500501)

A total petroleum system (TPS)—the Cretaceous-Tertiary Composite TPS— is defined within the Eastern Oregon and Washington Province (fig. 18); it includes thick successions of Cretaceous to Oligocene fluvial to deltaic arkosic sandstone and interbedded mudstone, carbonaceous shale, and coal. These strata are in (1) the Eocene Swauk Formation, Manastash Formation, Teanaway Formation, Chumstick Formation, and Roslyn Formation (fig. 5) and the Oligocene Wenatchee and Ohanapecosh Formations in Washington; and (2) the Cretaceous Hudspeth and Gable Creek Formations, the Paleocene to Eocene “Herren formation” of Shorey (1976), and the Eocene to lower Oligocene Clarno Formation in Oregon. The TPS most likely underlies much of the Eastern Oregon and Washington Province (fig. 18) and extends westward under the Cascade Range (fig. 19) obscuring and (or) separating many of the stratigraphically equivalent basins containing potential Paleogene hydrocarbon source rocks in both Oregon and Washington. The actual province boundary is defined on the basis where potential reservoir and source rocks are known to exist or inferred to exist and where hydrocarbon source rock thermal maturities have reached a vitrinite reflectance (R_o) of 0.5 percent or greater. Gas generated from potential hydrocarbon source rocks is interpreted to have migrated into Paleocene to Miocene reservoir rocks.

The Chuckanut Formation (fig. 20) in the Bellingham Basin and coal field (figs. 19, 20) may be stratigraphically equivalent to the Swauk, Roslyn, Naches, and Chumstick Formations (Johnson, 1985). Johnson (1984b) inferred a rapidly uplifted crystalline source area to the east, but the arkosic sandstone petrography of the Chuckanut Formation compared to the Swauk, Roslyn, Naches, and Chumstick Formations is similar (Frizzell, 1979; Johnson, 1984a; Johnson, 1985) indicating a probable connection between the basins. Frizzell (1979) also suggested that the Chuckanut and Swauk Basins might have been joined, then later separated by the Straight Creek fault zone (fig. 6). Other equivalent rocks of the Roslyn Formation extend westward under the Cascade Range to emerge in western Washington as the Puget Group (fig. 20) in the Green River coal field (fig. 19), the Carbonado Formation in the Wilkeson-Carbonado coal field, and the Cowlitz and Skookumchuck Formations (Vine, 1969; Johnson and others, 1997) in the Centralia-Chehalis coal field (figs. 19, 20). The coal-bearing strata accumulated in intertidal and deltaic environments along a tidally influenced delta plain (Brownfield and others, 1994; Flores and Johnson, 1995; Brownfield and others, 2005). The lower to middle Eocene Manastash Formation (fig. 5), in part, may be equivalent to the lower part of the Chuckanut Formation (Johnson, 1984a, fig. 20).

Equivalent rocks to the middle Eocene to Oligocene Clarno Formation and the “Herren formation” of Shorey (1976) may extend under the Cascade Range, in part, as the Fisher Formation (Beaulieu, 1972; fig. 20). The Clarno Formation and underlying “Herrin” rocks correlate, in part, with the fluvial to marginal marine Spencer Formation in west-central Oregon and the deltaic Coaledo Formations of southwestern Oregon (fig. 20). The upper Eocene Spencer contains lignite, coal, and carbonaceous shale in the upper parts of the unit (Beaulieu, 1971). The middle to upper Eocene Coaledo Formation in the Coos Bay coal field (fig. 19) contains numerous coal beds (Brownfield, 1981). Currently, coalbed methane exploration is ongoing in the Coos Bay areas

Figure 14. Exposure of volcaniclastic rocks of the Clarno Formation near Clarno, Oreg. (see fig. 9). The formation contains volcanic and volcaniclastic rocks and related nonmarine rocks as much as 5,800 ft thick (Waters and others, 1951; Peck, 1964). McCae Ranch is in the foreground and the John Day River is below the ridge-forming Clarno Formation.

Figure 15. Exposure of fluvial and lacustrine volcaniclastic rocks and cliff-forming mudflows (lahars) of the Clarno Formation, with the basal red ash beds of the John Day Formation in the background; view is at Camp Hancock near Clarno, Oreg. (see fig. 9). The Clarno nut bed fossil site, just below the cliff-forming volcanic mudflow, contains at least 140 different plant genera (Manchester, 1981) and is considered one of the best Eocene fossil flora sites in the world.

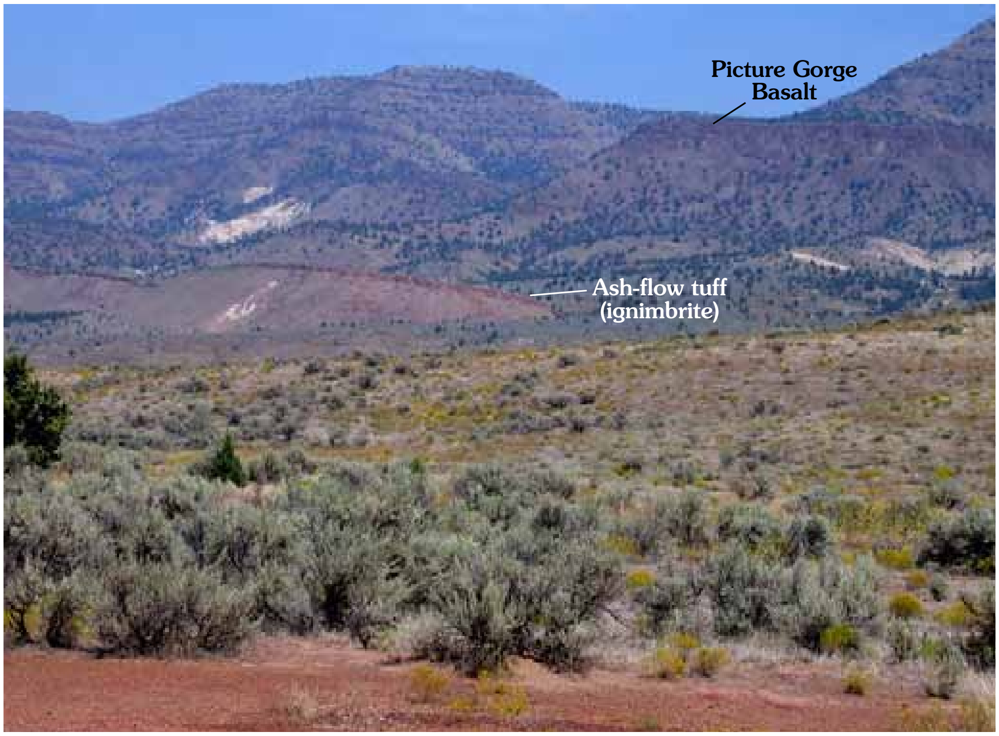

Figure 16. Exposure of volcaniclastic rocks of the John Day Formation in the Painted Hills Unit of the John Day Fossil Beds National Monument, Oreg. Basal red altered ash beds of the lower unit of the John Day Formation are in foreground, ash-flow tuff (ignimbrite) caps the ridge in middle ground, and the gray to white upper unit exposed near base of the slopes in background underlies the Picture Gorge Basalt of the Columbia River Basalt Group toward skyline (see fig. 8). The regionally extensive ignimbrite divides the John Day Formation into two units.

Figure 17. Exposure of zeolitic altered volcanic ash beds of the John Day Formation northeast of Mitchell, Oreg. Alteration to heulandite, clinoptilolite, and clay minerals is widespread. The green ash beds are overlain by a regionally extensive ash-flow tuff (ignimbrite) at least 50 ft thick (reddish, cliff forming unit near top of outcrop), that divides the John Day Formation into two units.

Figure 18. Areas of the Eastern Oregon and Washington Province in north-central and northeastern Oregon and eastern Washington (red outline), the Cretaceous-Tertiary Composite Total Petroleum System (blue outline), and the Rattlesnake Hills gas field. Coalbed methane exploration is ongoing in the Coos Bay area of Oregon in the Coaledo Formation (see figs. 19, 20).

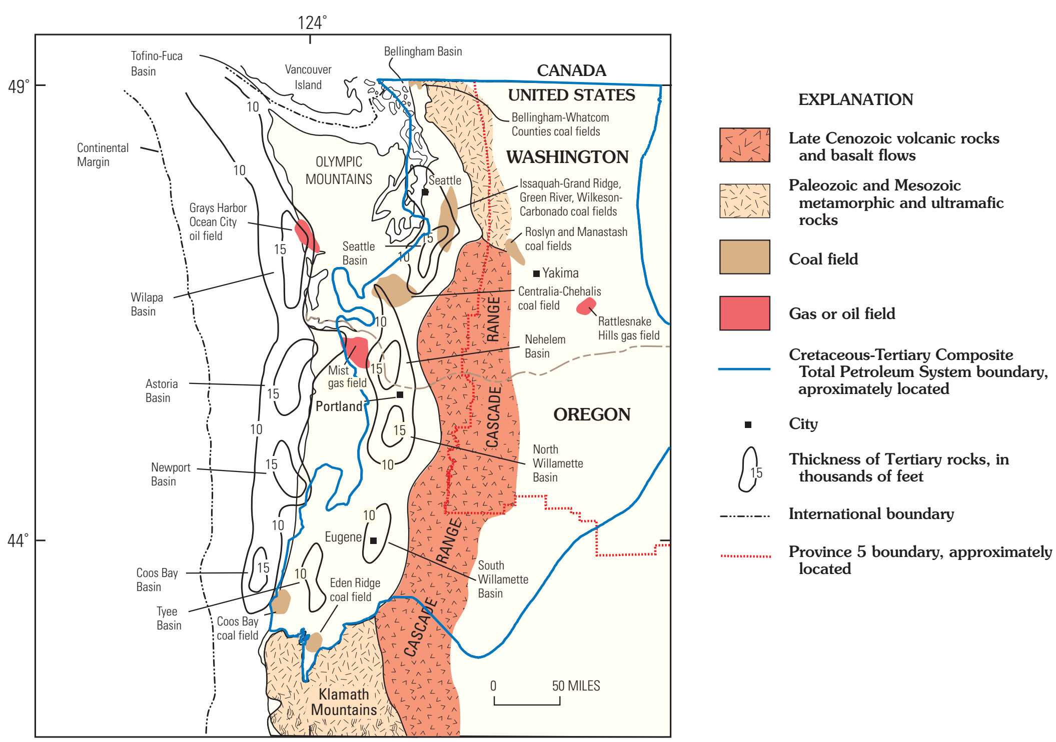

Figure 19. Location map showing selected Tertiary basins of western Oregon and Washington, the western part of the Eastern Oregon and Washington Province, most of the Cretaceous-Tertiary Composite Total Petroleum System (blue outline), and the approximate locations of oil and gas fields and Eocene coal fields. Isopach contours of Tertiary rocks are in thousands of feet. Modified from Armentrout and Suek (1985).

in the Coaledo Formation (figs. 18, 20). The upper middle Eocene Tyee Formation (fig. 20) in the southern part of Coos County (fig. 1), southeast of the Coos Bay coal field, contains coal beds in the Eden Ridge coal field (fig. 19) and may be equivalent, in part, to the Clarno Formation (Beaulieu, 1971).

An events chart (fig. 21) for the Cretaceous-Tertiary Composite TPS graphically portrays the ages of source, seal, and reservoir rocks, as well as the timing of trap development and generation, migration, accumulation, and preservation of hydrocarbons, and the critical moment that marks the beginning of hydrocarbon generation and migration.

The Paleocene to Eocene fluvial arkosic sandstones and interbedded mudstones and coals are widespread, although restricted to disconnected sub-basalt basins throughout the Eastern Oregon Washington Province (Frizzell, 1979; Walker, 1980; Tabor, Waitt, and others, 1982; Tabor and others, 1984; Johnson, 1984a; Tennyson and Parrish, 1987; Tennyson, 1995). In central Washington, for example, Eocene nonmarine arkosic sedimentary rocks exceed 20,000 ft in thickness in the northwest-trending Chiwaukum graben (fig. 6; Gresens and others, 1981; Evans, 1991) and are as much as or more than 25,000 ft thick in the Swauk Basin (Tabor and others, 1984; Taylor and others, 1988; Tabor and others, 1993; Tabor and others, 2000). Nonmarine arkose, mudstone, coal and volcanic rocks, with thicknesses ranging from 5,000 ft to more than 10,000 ft, are present below the late Tertiary to Quaternary volcanic cover in central Washington and north-central Oregon (figs. 5, 6, 9). A cross section drawn north of Yakima (figs. 6, 7), showing formations, hypothetical faults, and exploration holes, represents an interpretation of the Columbia Basin, central Washington, as a rift-graben structure (fig. 7). Campbell (1989) reported that the early to middle Tertiary section below the Columbia River Basalt Group may be as much as 23,000 ft thick near Yakima, Wash. (fig. 6).

Hydrocarbon source rocks include lacustrine shales in the Eocene Swauk and Chumstick Formations and coals in the Eocene Manastash, Naches, and Roslyn Formations (fig. 5). The lower to middle Eocene Swauk and Chumstick Formations contain lacustrine source rocks with total organic content (TOC) values of 0.03 to 1.10 weight percent and 0.13 to 5.97 weight percent, respectively (Lingley and Walsh, 1986; Tennyson, 1995). Vitrinite reflectance (R_o) values in outcrop samples of the Swauk Formation range from 0.82 to 1.29 percent, whereas the Chumstick Formation R_o values range from 0.25 to 0.89 percent (Johnson and others, 1997; Lingley and Walsh, 1986; Tennyson, 1995). The upper

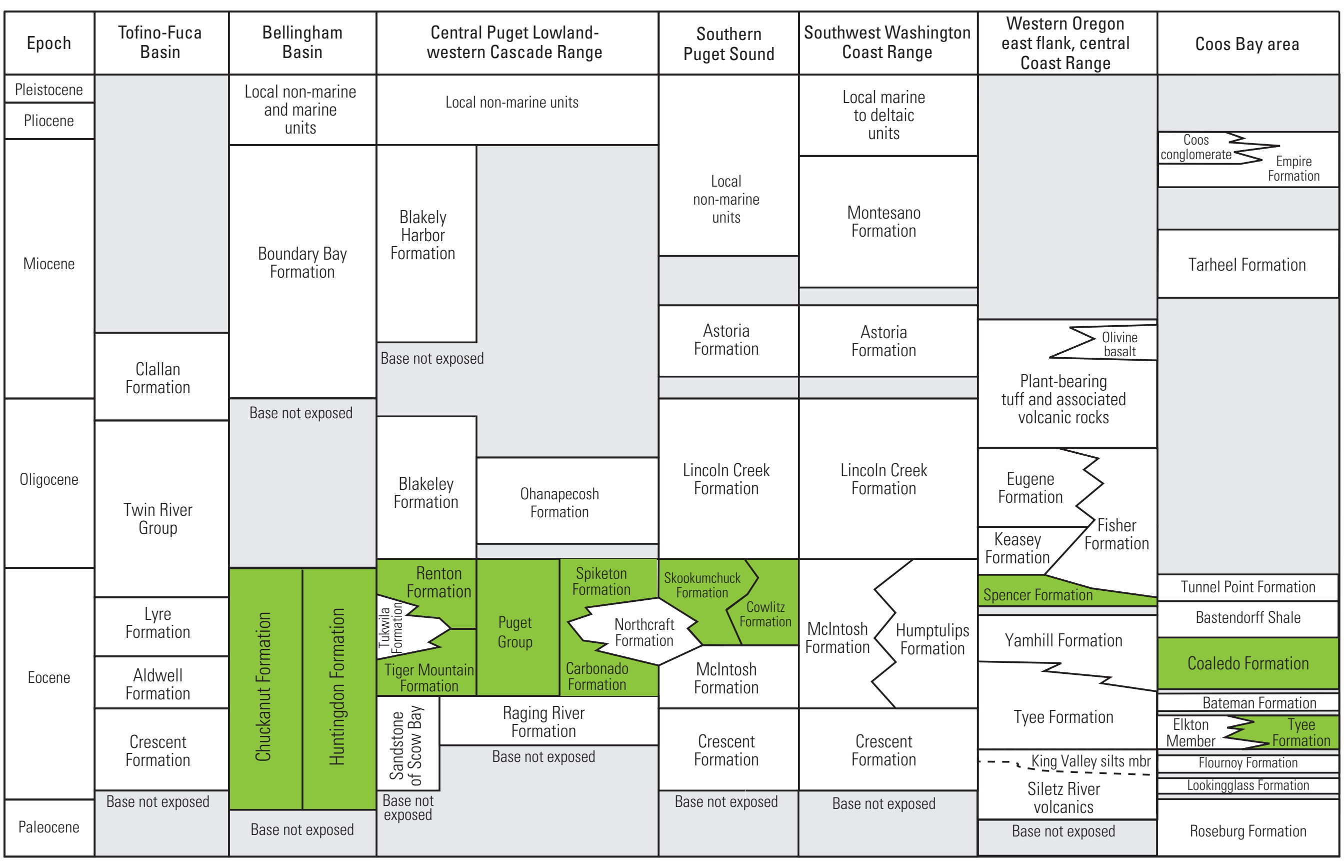

Figure 20. Stratigraphic correlation chart for western Oregon and Washington showing selected Tertiary units. Light-shaded intervals indicate intervals of erosion or nondeposition. Coal-bearing units are highlighted in green. The Tyee Formation southeast of the Coos Bay area contains coal in the Eden Ridge coal field (see fig. 19; Brownfield, 1981). Modified after Braislin and others (1971), Armentrout and Suek (1985), and Johnson and others (1997).

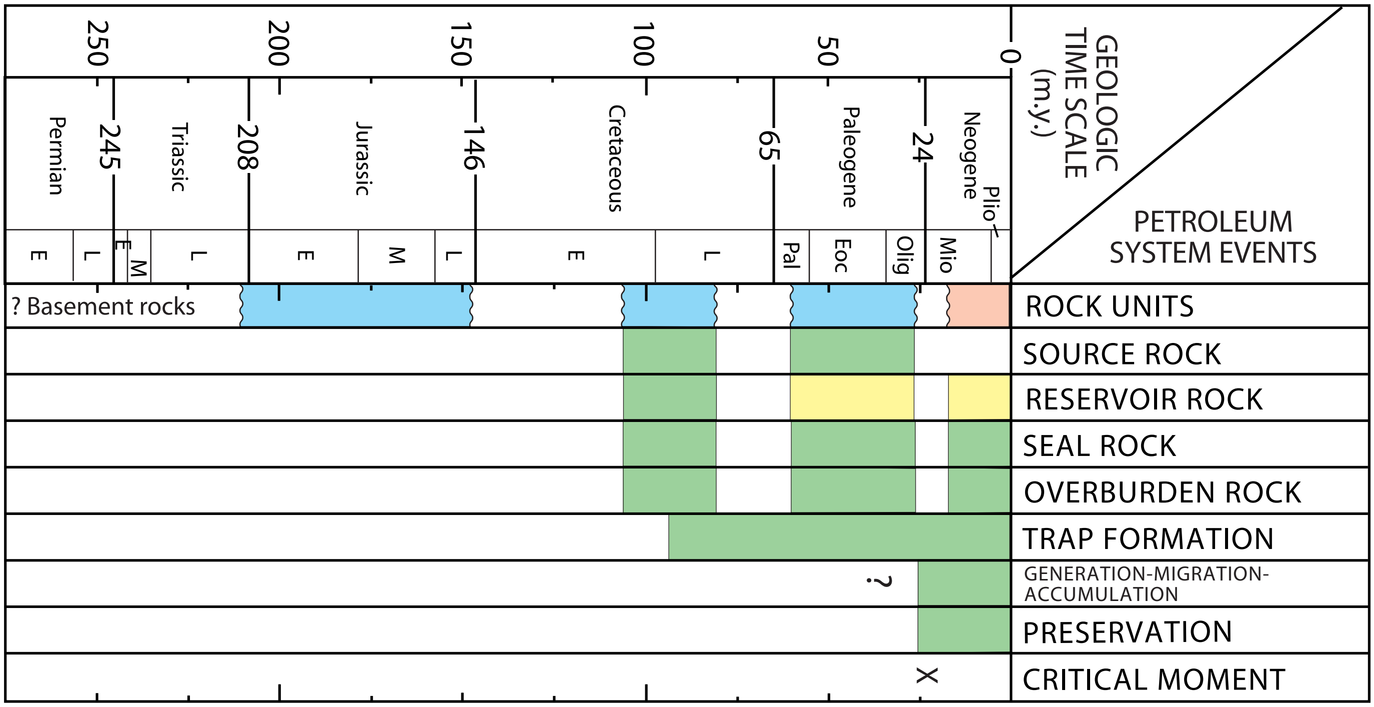

Figure 21. Events chart for the Cretaceous-Tertiary Composite Total Petroleum System in the Eastern Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and the time of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Critical moment is defined as the beginning of hydrocarbon generation and migration.

Eocene Roslyn Formation is about 9,000 ft thick in the Shell Bissa 1-29 exploration well (fig. 6; Campbell and Banning, 1985; Johnson and others, 1997), and the Roslyn Formation contains at least 30 coal beds (Walker, 1980) greater than 1 ft thick in the Roslyn coal field (fig. 6). Reported TOC values are 0.92 to 17.9 weight percent (Tennyson, 1995; Johnson and others, 1997) and the R_o values from subsurface coal samples range from 0.45 to 1.38 percent (Lingley and Walsh, 1986). The maximum vitrinite reflectance values from the sub-basalt section in two exploration wells, the Shell Burlington Northern 1-9 (R_o maximum of 1.32 percent) and Shell Yakima Minerals 1-33 (R_o maximum of 1.38 percent), indicate that the coals could have generated gas (Lingley and Walsh, 1986). The Manastash Formation source rocks consist of coals from 1 to 14 ft thick and carbonaceous shale (Saunders, 1914; Brownfield and Affolter, 1996).

Modeling of burial history, thermal maturity, and timing of hydrocarbon generation using Lopatin methodology by Tennyson and Parrish (1987) for the Yakima 1–33 exploration well (fig. 22) indicate that maturation of upper Eocene (Roslyn Formation) hydrocarbon source rocks probably began during the Miocene, following burial by the Columbia River Basalt Group (CRBG). Based on the model, hydrocarbon generation could have been as early as the uppermost Oligocene for the lower Eocene Swauk Formation (Tennyson and Parrish, 1987). Vitrinite reflectance values from coal samples analyzed from the Yakima 1-33 well (Lingley and Walsh, 1986) fit the burial history plot (fig. 22). One-dimensional modeling of burial history, thermal maturity, and hydrocarbon generation was performed on the Shell Burlington Northern 1-9 well (fig 6; fig. 23), using PetroMod1D Express (version 1.1) of Integrated Exploration Systems GmbH (IHS), Germany. The modeling confirms that maturation of upper Eocene (Roslyn Formation) hydrocarbon source rocks probably began during the Miocene following burial by the CRBG. The marginally thermally mature sedimentary interbeds in the lower part of the CRBG, reported by Lingley and Walsh (1986), are consistent with Miocene maturation.

In the northern part of the Cretaceous-Tertiary Composite Total Petroleum System (TPS), hydrocarbon traps are most likely large Miocene and younger folded and faulted structures. The Columbia River Basalt Group (CRBG) flows and sedimentary units were contemporaneously folded by north to south compression (Reidel, Fecht, and others, 1989) within the Yakima fold belt (fig. 6), beginning at or just before the initiation of CRBG volcanism; magnetotelluric data (Berkman and others, 1987) seem to confirm that a contemporaneous anticline existed northwest of Pasco, Wash. (fig. 6), centered on the Rattlesnake Hills gas field. Stratigraphic and structural traps in the Paleogene rocks below the CRBG are likely, but they would be difficult to detect.

Reservoir rocks are most likely fluvial sandstones in the Eocene Swauk, Roslyn, and Chumstick Formations, or in the Oligocene Wenatchee Formation. Porosities ranging from

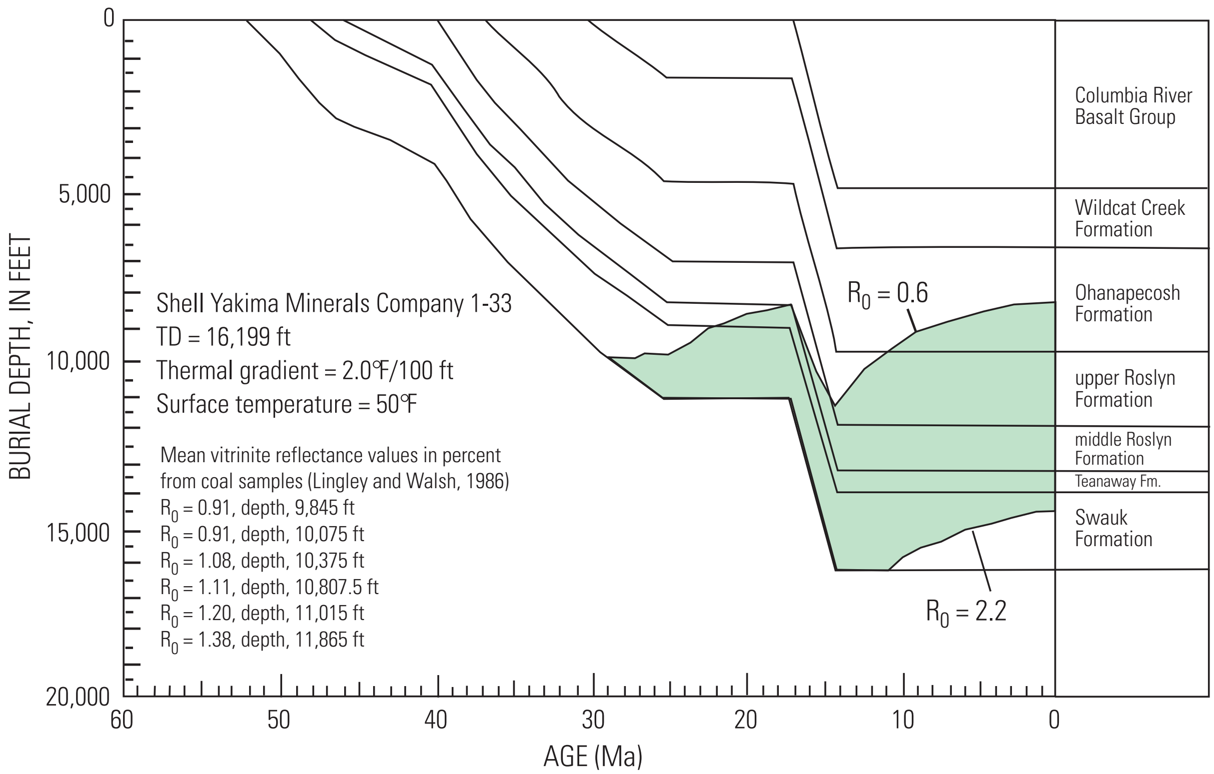

Figure 22. Burial history curve for Shell Yakima Minerals Company 1-33 exploration well (figs. 6, 7) with superimposed hydrocarbon generation window (green shading) using Lopatin methodology with time temperature indexes (TTI) equivalent to vitrinite reflectance (R_0) values 0.06 percent (TTI=10) and 2.2 percent (TTI=1,500), respectively. Plot was constructed assuming that no erosion occurred between units, but periods of nondeposition are represented by horizontal lines along the curve. Assumed surface temperature assumed is 50°F, with a geothermal gradient of 2.0°F/100 ft. The plot indicates that maturation of Swauk Formation source rocks could have begun in the Oligocene and that maturation of the Roslyn Formation source rocks probably began during the Miocene following burial by the Columbia River Basalt Group. Formation depths and thicknesses from Campbell and Banning (1985). Modified from Tennyson and Parrish (1987). Fm., Formation.

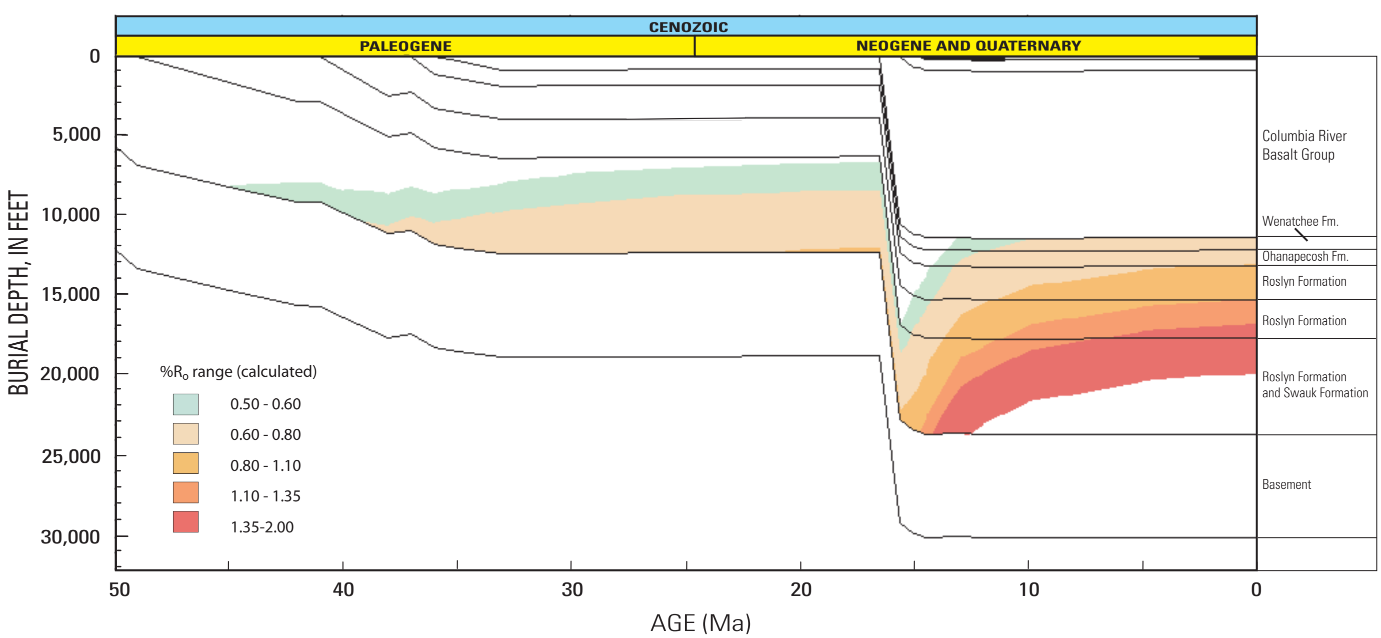

Figure 23. Burial history curve for the Shell Burlington Northern 1-9 well (figs. 6, 7) using PetroMod1D Express (version 1.1) of Integrated Exploration Systems GmbH (IHS), Germany, with superimposed calculated vitrinite reflectance values from L.N.R. Roberts (written commun., 2007). Fm., Formation.

3.9 to 22.1 percent were reported from samples analyzed from several deep wells (Lingley and Walsh, 1986; Walsh and Lingley, 1991: Myer, 2005; Wilson and others, this volume). Many of the potential reservoir sandstones contain volcaniclastic grains that have been altered to clays and zeolites, reducing the porosity (Lingley and Walsh, 1986; Tennyson, 1995; Wilson and others, 2007). Vesicular basalt flows within the CRBG, such as the flows described at the Rattlesnake Hills gas field, are also potential reservoirs (McFarland, 1979). Johnson and others (1993) reported gas in basalt aquifers. Seal rocks are shale interbeds or altered volcaniclastic rocks in the Paleogene section or within the CRBG.

In the southern part of the TPS, gas-prone source rocks include (1) marine shales of the Cretaceous Hudspeth Formation; and (2) coals, carbonaceous shales, and lacustrine shales in the Paleogene "Herren formation" of Shorey (1976) and the Clarno Formation (fig. 5). The Hudspeth contains marine shale, but the overall northern extent of Cretaceous strata is unknown. Sidle and Richers (1985) reported that the Hudspeth Formation contains mixed marine kerogen with a strong terrigenous component in some samples. Reported TOC values are 0.21 to 3.7 weight percent (Fisk and Fritts, 1987; Law and others, 1984; Sidle and Richers, 1985). Law and others (1984) reported R_o values ranging from 0.61 to 0.84 percent for surface samples, and Fisk and Fritts (1987) reported an average R_o value of 0.99 percent; such values indicate that Hudspeth source rocks are thermally mature, or marginally so. Sidle and Richers (1985) reported values for the temperature at the peak of hydrocarbon generation (T_{max}) that suggested a trend from post-mature (gas) southeast of Mitchell, Oreg. (fig. 9) to mature (oil to gas) northwest of Mitchell for the Hudspeth Formation. Newton (1979) reported a mean R_o value of 1.04 percent and a TOC value of 0.80 weight percent for 40 samples collected from an 8-ft interval of Jurassic-Cretaceous rocks (depth, 8,385 to 8,393 ft) in the Standard Kirkpatrick 1 well (Fox and Reidel, 1987b). Vitrinite reflectance profiles from exploration wells penetrating Cretaceous rocks that may, in part, be equivalent to the Hudspeth and Gable Creek Formations (informally called the Mitchell formation by Fisk and Fritts, 1987) are rare in the southern part of the Cretaceous-Tertiary Composite TPS. The Texaco Logan Butte 17-1 well (fig. 9) has a consistent profile, where the entire sedimentary column roughly matured to a R_o value of 1.11 percent (range, 1.11 to 1.18 percent; Summer and Verosub, 1992); depth of the analyzed samples ranged from 1,800 ft to 6,400 ft. The R_o profile for the Sunray Bear Creek 1 well (fig. 9) is more complex because of the presence of an intrusive sill at a depth of 4,890 ft, which increases the underlying R_o values. The R_o values range from 0.78 percent about 920 ft above the sill to 1.4 percent below the sill; the deepest (6,340 ft) sample has a value of 1.3 percent. Both wells penetrated Cretaceous rocks, and Thompson and others (1984) suggested, on the basis of biostratigraphic data, that Albian to Campanian rocks were deposited in the basin; and Fritts and Fisk (1985a,b) indicated that they are equivalent to the Jurassic-Cretaceous fore-arc rocks in the northern part of the province. Summer and Verosub (1987, 1992)) interpreted a regional hydrothermal event about 22 Ma to have caused maturation of the Cretaceous rocks. The vitrinite reflectance values and the postulated regional hydrothermal event indicate that the Cretaceous source rocks are likely mature and potentially could have generated gas.

The upper Eocene to lower Oligocene Clarno Formation is as much as 6,000 ft thick and includes the "Herren formation" of Shorey (1976). Both units contain carbonaceous and lacustrine shales and coals, with reported TOC values of 0.17 to 4.47 weight percent and 0.04 to 23.9 weight percent, respectively (Law and others, 1984; Kuo, 1988). Subsurface samples yielded R_o values of 0.33 to 0.85 percent (Kuo, 1988). Samples analyzed from the Standard Kirkpatrick 1 well (fig. 9; depth 6,005-8,668 ft) yielded R_o values ranging from 1.01 to 1.15 percent from pre-Clarno rocks (Summer and Verosub, 1992); this is the only well to penetrate the Columbia River Basalt Group in the southern part of the Cretaceous-Tertiary Composite TPS north of the Blue Mountains anticlinorium (fig. 9).

Burial of the postulated Hudspeth and "Herren formation" source rocks beneath thick sections of Eocene to Miocene rocks is most likely necessary for maturation to have occurred in the southern part of the total petroleum system. A cross section, modified from Fritts and Fisk (1985b), drawn across the Blue Mountains anticlinorium (fig. 24), shows Hudspeth and "Herren formation" rocks that may contain hydrocarbon source rocks at depths sufficient for maturation and the generation of hydrocarbons. A high geothermal gradient is likely throughout the southern part of the province, and R_o values were interpreted (Summer and Verosub, 1987, 1992) as evidence of a high hydrothermal event having occurred there during the late Oligocene, which caused the maturation of hydrocarbon source rocks with hydrothermal fluids. Migration most likely occurred during the latest Oligocene or earliest Miocene and may continue today.

In the northernmost part of central Oregon, hydrocarbon traps are most likely large Miocene and younger folds and faults (fig. 9). The CRBG flows and sedimentary strata have been contemporaneously folded (Reidel, Fecht, and others, 1989) within the southernmost part of the Yakima fold belt (fig. 6) north of the Blue Mountains anticlinorium (fig. 9). Stratigraphic and structural traps in the Paleogene rocks are postulated both below the CRBG and south of the Blue Mountains anticlinorium (fig. 9).

Potential Cretaceous marine sandstones in the Gable Creek Formation have low porosity and permeability in surface outcrop samples (Riddle, 1990), but may have some reservoir potential to the southwest where log analyses of the Sunray Bear Creek 1 and Texaco Logan Butte 17-1 wells (fig. 9) indicate that porosity and permeability may have been preserved ((Fritts and Fisk, 1985b); this may also be true to the north, although the northern extent of the Cretaceous rocks is unknown. Porosity values of Gable Formation reservoir rocks (Mitchell formation, Fisk and Fritts, 1987) range from 3.0 to

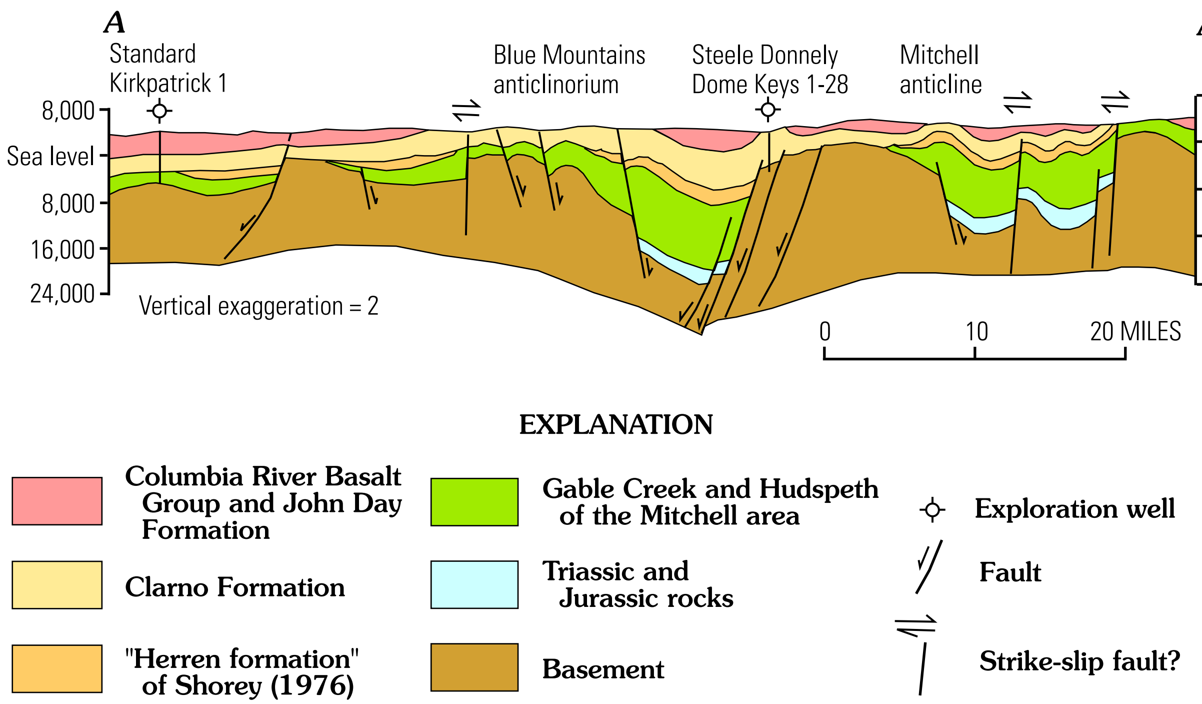

Figure 24. Northwest to southeast cross section across the Blue Mountains anticlinorium in north-central Oregon, with faulted pre-Tertiary basement rocks overlain by Paleocene to Oligocene, largely fluvial and volcaniclastic strata, and by the Oligocene John Day Formation and the Miocene Columbia River Basalt Group. Not to scale. Cross section represents an interpretation for the southern part of the Eastern Oregon and Washington Province as a rift-graben structure. See figure 9 for location of cross section. Modified from Fritts and Fisk (1985b).

11.0 percent, with an average of 7.0 percent (Fisk and Fritts, 1987). Reservoir rocks are postulated to be in the Paleocene and Eocene “Herren formation” of Shorey (1976) and the Eocene to lower Oligocene Clarno Formation and consist of arkosic fluvial sandstones. The “Herren” arkosic sandstones are reported to have porosities ranging from 8 to 21 percent, with an average of 12 percent (Fisk and Fritts, 1987; Riddle, 1990), and permeabilities ranging from 0.4 to 73 mD (millidarcies) (average 8 mD). Potential reservoir rocks in the Clarno Formation have porosities ranging from 4 to 38 percent, with an average17 percent (Fisk and Fritts, 1987; Riddle, 1990), and permeabilities as much as 43 mD (average 8 mD). North of the Blue Mountains anticlinorium (fig. 9) in northernmost Oregon, vesicular basalt flows within the CRBG at the Rattlesnake Hills gas field (McFarland, 1979), are also potential reservoirs. Seal rocks are most likely interbedded Cretaceous shales or Paleogene fluvial-deltaic and lacustrine shales and altered volcaniclastic rocks and ash beds.

The abandoned Rattlesnake Hills gas field (Hammer, 1934) is included in Cretaceous-Tertiary Composite TSP (fig. 18). This field was discovered in 1913 and produced about 1.3 BCFG before it was abandoned in 1941 (McFarland, 1979). Production was from two vesicular basalt zones sealed by sedimentary interbeds less than 2,000 ft deep within the CRBG. The gas probably was generated from the underlying Eocene coals (Johnson and others, 1993), and was mostly methane with about 10 percent nitrogen (Wagner, 1966). Johnson and others (1993) reported that the gas in the basalt aquifers was thermogenic. Several deep exploration wells have tested the sedimentary section below the CRBG in the north-central part of the TPS area and encountered noncommercial gas shows (fig. 6). One well northeast of Mitchell, Oreg., the Steele Energy Keys 1-28 well (fig. 9), flowed at a rate of 2,650 barrels of water per day (BWPD) and producing 4 million cubic feet of gas (MMCFG) over a 3-month period from Clarno Formation (Summer and Verosub, 1992). Other indications that hydrocarbons have been generated include asphalt-filled fractures and cavities reported in several outcrops in central Oregon, one oil-filled geode (Sidle and Richers, 1985), and gas shows in water wells.

Assessment Units of the Eastern Oregon and Washington Province

Three assessment units (AU) were defined within the Cretaceous-Tertiary Composite TPS: (1) the Eastern Oregon and Washington Conventional Gas AU; (2) the Columbia Basin Continuous Gas AU; and (3) the Republic Graben Gas AU. Undiscovered gas resources within (1) and (2) were quantitatively estimated, but (3) was not assessed.

The gas accumulations in the Columbia Basin Continuous Gas AU are of the continuous type (unconventional) and were defined using criteria established by Schmoker (1999). Gas accumulations in the Eastern Oregon and Washington Conventional Gas AU are of the conventional type and were defined using the criteria established by Schmoker and Klett (1999).

Based on a play concept (rather than an assessment unit concept), Tennyson (1996) assessed the undiscovered conventional gas in two plays within the Eastern Oregon and Washington Province: (1) the hypothetical Northwestern Columbia Plateau Gas Play, with an estimated mean of 235.1 BCFG; and (2) the hypothetical Central and Northeastern Oregon Paleogene Gas Play, with an estimated mean of 78.4 BCFG. Law (1996) assessed a hypothetical continuous gas accumulation in the province, the Columbia Basin-Centered Gas Play, with an estimated mean of 12.2 trillion cubic feet of gas (TCFG) and 122 million barrels of natural gas liquids (MMBNGL).

Eastern Oregon and Washington Conventional Gas Assessment Unit (50050101)

The hypothetical Eastern Oregon and Washington Conventional Gas Assessment Unit (AU) is defined within the Cretaceous-Tertiary Composite TPS. This AU includes thick successions of Cretaceous to Oligocene marine sandstone and shale and fluvial to deltaic arkosic sandstone and interbedded mudstone, carbonaceous shale, and coal. Its limits are defined on the basis of where potential reservoir and source rocks are known or inferred to exist and where hydrocarbon source rock thermal maturities have reached a vitrinite reflectance (R_o) of 0.5 percent or greater (fig. 25). Normal-pressured gas generated from potential hydrocarbon source rocks would have migrated to Paleogene to Miocene reservoir rocks. These units are widespread throughout the Eastern Oregon and Washington Province but in many places are overlain by the Miocene Columbia River Basalt Group (CRBG) and other Miocene to Quaternary volcanic rocks (figs. 6, 7, 9). A hypothetical cross section was drawn across the northern part of the AU (figs. 6, 7) showing formations, hypothetical faults, and exploration holes and represents an interpretation of the Columbia Basin, central Washington, as a rift-graben structure.

The Eastern Oregon and Washington Conventional Gas AU likely underlies much of the Eastern Oregon and Washington Province (fig. 25) and extends southwestward across the province boundary; it contains more than 22.2 million acres. The gas accumulations in this AU are of the conventional type and were defined using the criteria established by Schmoker and Klett (1999).

Events charts (figs. 26, 27) for the northern and southern parts of the Eastern Oregon and Washington Conventional Gas AU graphically portray the ages of source, seal, and reservoir rocks, timing of trap development, generation, accumulation, migration, and preservation of hydrocarbons, and the critical moment that marks the onset of hydrocarbon generation and migration.

In the northern part of the AU, boundaries are somewhat hypothetical, because they depend on the inferred presence of sedimentary rocks beneath the basalt. The northeast boundary is the hypothetical projection of the Entiat fault (fig. 6), which forms the northeast boundary of the Chiwaukum graben, whereas the eastern boundary is approximated to be the limit of thick sedimentary rocks beneath the basalt. The northwest boundary is the western outcrops of the Eocene Roslyn and Swauk Formations, and the western boundary is drawn west of the last inliers of Eocene sedimentary rocks within the basalt. In the southern part of the AU the boundaries, are drawn on the basis of where potential reservoir and source rocks are known or inferred to coexist (fig. 9).

Modeling of burial history, thermal maturity, and timing of hydrocarbon in the northern part of the Eastern Oregon and Washington Conventional Gas AU by Tennyson and Parrish (1987) for the Shell Yakima Minerals 1-33 exploration well (figs. 6, 22) and recent modeling (L.N.R. Roberts, written commun., 2007) for the Shell Burlington Northern 1-9 (figs 6, 23) indicate that maturation of upper Eocene (Roslyn Formation) hydrocarbon source rocks probably began during the Miocene following burial by the

Figure 25. Area of the Eastern Oregon and Washington Province in north-central and northeastern Oregon and eastern Washington red outline), boundaries of the Cretaceous-Tertiary Total Petroleum System (green outline) and Eastern Oregon and Washington Conventional Gas Assessment Unit (50050101; blue outline), and the location of the Rattlesnake Hills gas field.

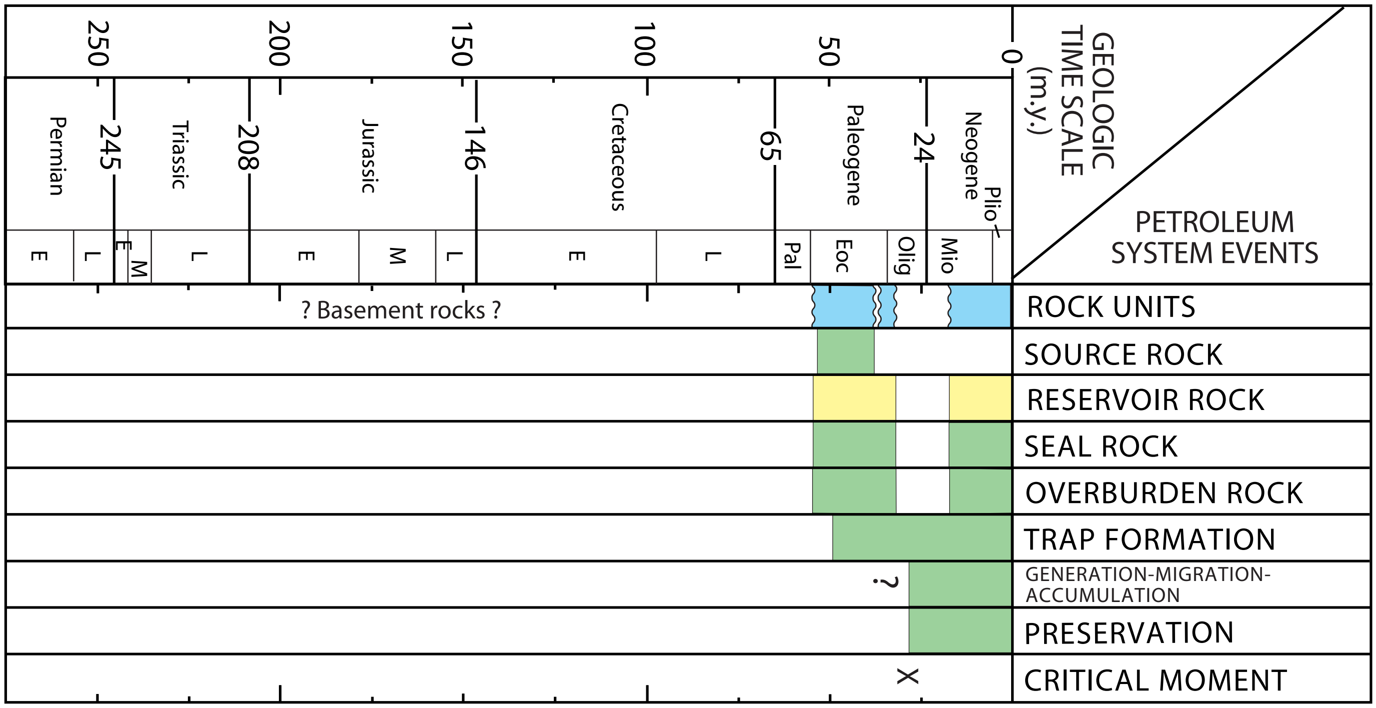

Figure 26. Events chart for the northern part of the Eastern Oregon and Washington Conventional Gas Assessment Unit (50050101) in the Eastern Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and times of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Critical moment is defined as the beginning of hydrocarbon generation and migration.

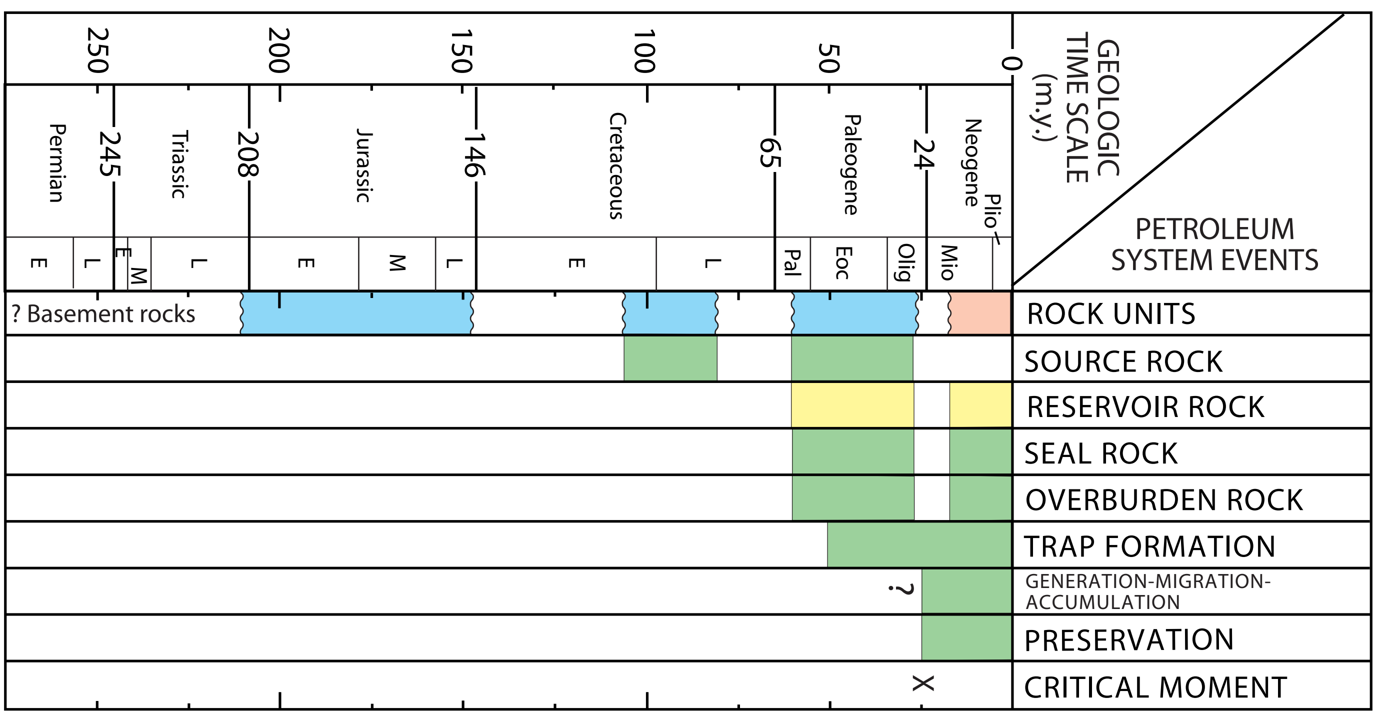

Figure 27. Events chart for the southern part of the Eastern Oregon and Washington Conventional Gas Assessment Unit (50050101) in the Eastern Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and times of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Critical moment is defined as the beginning of hydrocarbon generation and migration.

Columbia River Basalt Group. Maturation could have been as early as the Oligocene (fig. 22) for the lower Eocene Swauk Formation (Tennyson and Parrish, 1987). Vitrinite reflectance values from coal samples analyzed from the two wells fit the calculated R_o values in the modeled wells (Lingley and Walsh, 1986).

Burial of postulated Hudspeth Formation and the “Herren formation” hydrocarbon source rocks beneath thick Eocene to Miocene volcanic units is most likely essential for maturation to have occurred in the southern part of the assessment unit. Analyzed samples for the Hudspeth Formation indicate that the potential source rocks are probably mature to overmature (Sidle and Richers, 1985; Fisk and Fritts, 1987), whereas the “Herren formation” source rocks are mature (Law and others, 1985; Fisk and Fritts, 1987). A cross section constructed across Blue Mountains anticlinorium (fig. 9) shows formations, hypothetical faults, and exploration holes (fig. 24). It represents an interpretation of the southern part of the Eastern Oregon Conventional Gas AU to be rift-graben structure (Fritts and Fisk, 1985b) and shows the postulated source-rock bearing-Hudspeth Formation and “Herren formation” to be buried below thick Eocene to Miocene volcanic rocks to depths sufficient for maturation and the generation of hydrocarbons (fig. 24). Cretaceous rocks penetrated in the Standard Kirkpatrick 1 well (Fritts and Fisk, 1985b; Fox and Reidel, 1987a, 1987b) near Condon, Oreg. (figs. 9, 24) may be a northern equivalent of the Cretaceous rocks at Mitchell, Oreg. A high geothermal gradient is likely throughout the southern part of the Eastern Oregon and Washington Province. Vitrinite reflectance values have been interpreted as evidence of a high geothermal gradient (Summer and Verosub, 1992) in the southern part of the TPS. During the late Oligocene, much of the area was subjected to a period of high heat flow, causing the maturation of hydrocarbon source rocks with hydrothermal fluids regionally (Summer and Verosub, 1987, 1992). Locally, thick successions of Clarno and John Day Formation rocks would have buried the Cretaceous Hudspeth Formation and Paleocene to Eocene “Herren formation” of Shorey (1976) to a sufficient depth to cause thermal maturation. Maturation and migration most likely began in the latest Oligocene and may continue today (fig. 27). Sidle and Richers (1985) conducted a soil-gas survey for light hydrocarbons (methane to butane) and observed a trend within the Clarno Formation that was interpreted to indicate that the maturation and migration of hydrocarbons occurred in north-central Oregon from a Cretaceous source.

In the northern part of the AU, the hydrocarbon traps are most likely large Miocene folds and faults associated with the Columbia River Basalt Group (CRBG). Flows and sedimentary rocks within the group have been contemporaneously folded (Reidel, Fecht, and others, 1989) in the Yakima fold belt (fig. 6). Stratigraphic traps consisting of Paleogene arkosic fluvial sandstones below the CRBG are likely but would be difficult to detect. Other possible traps include vesicular flows within the flood basalts and structural traps that formed below the CRBG in the deeper grabens (fig. 7). In the southern part of the AU, Miocene and younger folds and faults are possible traps, as are stratigraphic traps within the “Herren formation” of Shorey (1976) and the Clarno Formation.

In the northernmost part of central Oregon (fig. 9) and the southernmost part of the Yakima fold belt (fig. 6), north of the Blue Mountains anticlinorium (fig. 9), the traps are also expected to be large Miocene and younger folds and faults that formed in the CRBG flows and sedimentary strata contemporaneously (Reidel, Fecht, and others, 1989). Stratigraphic and structural traps in the Paleogene rocks are postulated both below the CRBG and south of the Blue Mountains anticlinorium (fig. 9).

In the northern part of the AU, reservoir rocks are arkosic fluvial sandstones in the Paleogene Swauk, Chumstick, Roslyn, and Wenatchee Formations in the Washington part of the AU. These strata range in thickness from 4,000 ft to more than 10,000 ft and have porosities as much as 13–16 percent, as reported from three wells (Lingley and Walsh, 1986). Many of the potential reservoir sandstones contain altered volcaniclastic grains, forming clays and zeolites that reduce the porosity (Lingley and Walsh, 1986; Tennyson, 1995; Wilson and others, this volume). Vesicular basalt flows within the Columbia River Basalt Group, such as those described at the Rattlesnake Hills gas field, are potential reservoirs (McFarland, 1979). The gas field produced at a depth of 2,000 ft from two vesicular zones sealed by sedimentary interbeds. Johnson and others (1993) reported gas in basalt aquifers.

In the southern part of the AU, potential Cretaceous marine reservoir sandstones of the Gable Creek Formation have low porosity and permeability in samples from outcrops (Riddle, 1990), but may have better reservoir potential to the southwest of Mitchell, Oreg., where analysis of well logs indicates that porosity and permeability may have been preserved (Fritts and Fisk, 1985b). Porosity values of Gable Formation reservoir rocks (Mitchell Formation, Fisk and Fritts, 1987) average 7.0 percent. Reservoir rocks are postulated to be in the Paleocene to Eocene “Herren” rocks of Shorey (1976) and Eocene to earliest Oligocene Clarno Formation, and consist of arkosic fluvial sandstones and lithic arkose and volcaniclastic sandstones, respectively. The “Herren” arkosic sandstones have porosities averaging 12 percent (Fisk and Fritts, 1987; Riddle, 1990) and permeabilities ranging from 0.4 to 73 mD (average 8 mD). The Clarno Formation reservoir rocks are reported to have porosities averaging about 17 percent (Fisk and Fritts, 1987; Riddle, 1990). North of the Blue Mountains anticlinorium (fig. 9), vesicular basalt flows within the CRBG, such as the flows described at the Rattlesnake Hills gas field, might be potential reservoirs (McFarland, 1979).

In the northern part of the AU, seal rocks are shale interbeds or altered volcaniclastic rocks in the Paleogene section or within the CRBG. In the southern part, seal rocks are most likely interbedded Cretaceous shales or Paleogene fluvial-deltaic and lacustrine shales and altered volcaniclastic rocks and volcanic ash beds.

In the northern part of the AU, depths to postulated reservoirs and traps range from less than 2,000 ft (the Rattlesnake Hills gas field) to more than 10,000 ft (fig. 7), where normal pressured gas exists. Hydrocarbon seals most likely consist of interbedded fluvial shales and altered volcaniclastic rocks and volcanic ash beds. In the southern part, depths to postulated reservoirs and traps are also about 2,000 ft to more than 10,000 ft (Appendix A).

The Rattlesnake Hills gas field (Hammer, 1934), which is included in this AU, was discovered in 1913 and produced about 1.3 billion cubic feet of gas (BCFG) until it was abandoned in 1941 (McFarland, 1979). The gas field produced at a depth of 2,000 ft from two vesicular zones sealed by sedimentary interbeds within the Columbia River Basalt Group; the gas, mostly methane containing about 10 percent nitrogen (Wagner, 1966), probably was generated from Eocene coals below the CRBG (Johnson and others, 1993) and migrated upward.

The hypothetical Eastern Oregon and Washington Conventional Gas AU currently has no gas production. It is given a geologic probability of 0.8 because of the uncertainty of having adequate reservoirs, traps, and seals (Appendix A). The estimated minimum, mode, and maximum number of undiscovered gas accumulations are 1, 5, 50, respectively, whereas the estimated minimum, median, and maximum size of undiscovered gas accumulations are 3, 10, and 500 BCFG, respectively.

The USGS assessed mean undiscovered volumes in the Eastern Oregon and Washington Conventional Gas AU of 305 billion cubic feet (BCF) of estimated conventional gas (table 1) and 0.61 million barrels of natural gas liquids (MMBNGL). The estimated mean size of the largest gas field is 78.3 BCFG, and the estimated gas volume (305 BCF) represents about 12 percent of the total estimated mean of 2,427 BCF of gas in the Eastern Oregon and Washington Province.

Columbia Basin Continuous Gas Assessment Unit (50050161)

The hypothetical Columbia Basin Continuous Gas AU (figs. 28, 29) is defined as having a continuous gas-bearing rock sequence that lies below the Columbia River Basalt Group and has vitrinite reflectance values (R_o) greater than 0.7 percent at a depth of about 9,800 ft; the gas-bearing interval ranges from 9,800 to more than 17,500 ft thick, potential reservoirs contain overpressured thermogenic gas, and bottom hole temperatures exceed the 190° to 200°F threshold for unconventional gas accumulations (Law and Dickinson, 1985; Spencer, 1989; Law and Spencer, 1993; Law, 2002). The overlying CRBG ranges from 4,000 ft to as much as 13,800 ft thick (Reidel, Fecht, and others, 1989) in the Pasco area (figs. 6, 29) and may be more than 15,000 ft thick (Berkman and others, 1987) northwest of Pasco (figs. 6, 29), based on magnetotelluric data. The AU contains more than 4 million acres. The gas accumulations in this AU are of the continuous type (unconventional) and were defined using the criteria established by Schmoker (1999).

An events chart (fig. 30) for the Columbia Basin Continuous Gas AU graphically portrays the ages of source, seal, and reservoir rocks, as well as timing of trap development, and generation, migration, accumulation, and preservation of hydrocarbons, and the critical moments. A critical moment is defined as the beginning of hydrocarbon generation and migration.

Because much of the AU is overlain by the Columbia River Basalt Group (fig. 29), the distribution of both Paleogene source and reservoir rocks is largely obscured. Schematic cross sections constructed through selected exploration wells that had gas shows (figs. 6, 7, 31, 32), using log-interpreted stratigraphic thicknesses (Wilson and others, this volume),

Table 1. Summary of estimated undiscovered volumes of conventional oil, gas, and natural gas liquids and of continuous gas for undiscovered oil and gas fields for the Eastern Oregon and Washington Province.

[MMBO, millions barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. Undiscovered gas resources are the sum of nonassociated and associated gas. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. TPS, Total Petroleum System; AU, Assessment Unit. Gray shade indicates not applicable]

Total Petroleum Systems *and Assessment Units*	Field type	*Total undiscovered resources* Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Cretaceous-Tertiary Composite TPS													
Eastern Oregon and Washington Conventional Gas AU	***Oil***	0	0	0	0	0	0	0	0	0	0	0	0
	Gas					0	242	857	305	0	0.41	1.94	0.61
Republic Graben Gas AU		*Not quantitatively assessed*											
Columbia Basin Continuous Gas AU	***Gas***					1,179	2,013	3,436	2,122	3.12	7.85	19.79	9.20
Total Undiscovered Oil and Gas Resources		**0**	**0**	**0**	**0**	**1,179**	**2,255**	**4,293**	**2,427**	**3.12**	**8.26**	**21.73**	**9.81**

Figure 28. Area of the Eastern Oregon and Washington Province (red outline) in north-central and northeastern Oregon and eastern Washington and the boundaries of Cretaceous-Tertiary Total Petroleum System (blue outline) and Columbia Basin Continuous Gas Assessment Unit (50050161; yellow outline), and the location of the Rattlesnake Hills gas field.

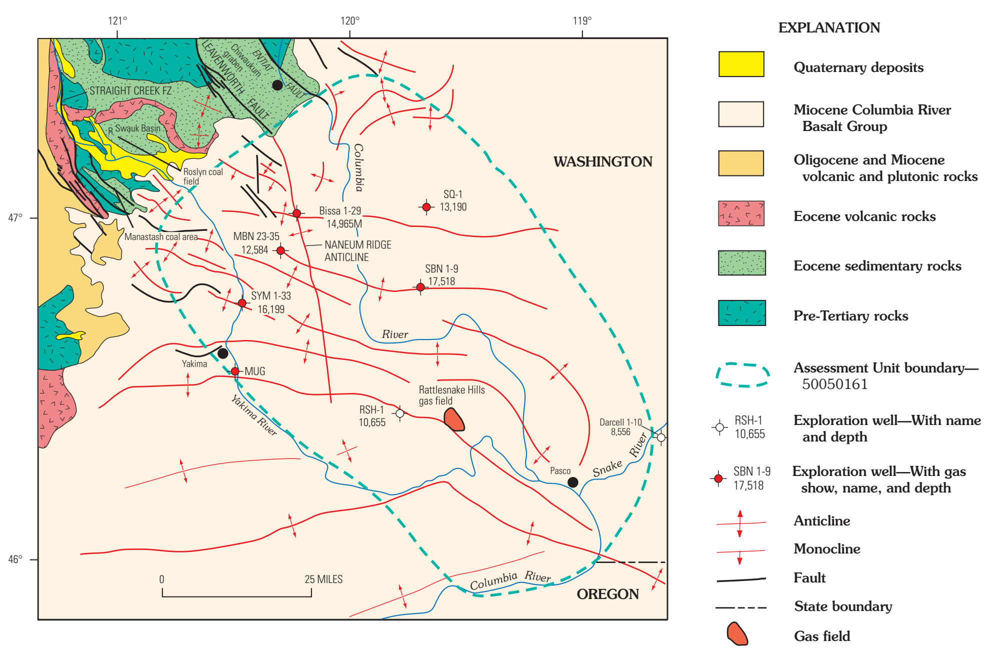

Figure 29. Generalized geology of the Columbia Basin showing outline of the Columbia Basin Continuous Gas Assessment Unit (50050161), defined as the overpressured gas-bearing interval below the Columbia River Basalt Group (CRBG) with vitrinite values greater than 0.7 percent. Also shown are geologic units, exploration wells, faults, fold axes, Roslyn coal field, and the Manastash coal area. The Yakima fold belt is generally located north and west of the Yakima River within CRBG. Darcell 1-10, Shell Darcell No. 1-10; FZ, Fault zone; R, Roslyn, SQ-1, Shell Quincy No. 1; SBN 1-9, Shell Burlington Northern 1-9; RSH-1, Standard Oil Rattlesnake Hills No. 1; MUG, Miocene Union Gap; SYM 1-33, Shell Yakima Minerals Company 1-33; MBN 23-35, Meridian Burlington Northern 23-35; Bissa 1-29, Shell Bissa 1-29; W, Wenatchee. Geology modified from Johnson and others (1993), and Campbell (1989).

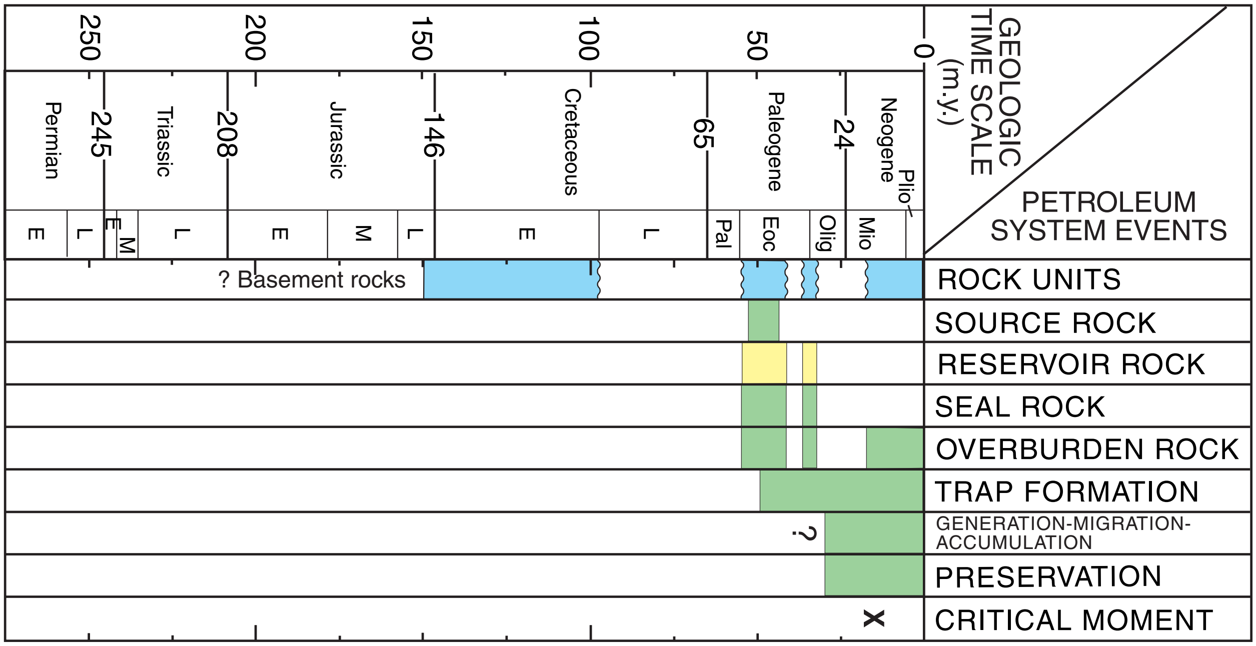

Figure 30. Events chart for the Columbia Basin Continuous Gas Assessment Unit (50050161) in the Eastern Oregon and Washington Province. Light blue indicates rock units present; wavy line, unconformity. Age ranges of source, seal, reservoir, and overburden rocks and times of trap formation and generation, migration, accumulation, and preservation of hydrocarbons shown in green and yellow. Queries indicate uncertainty. Critical moment is defined as the beginning of hydrocarbon generation and migration.

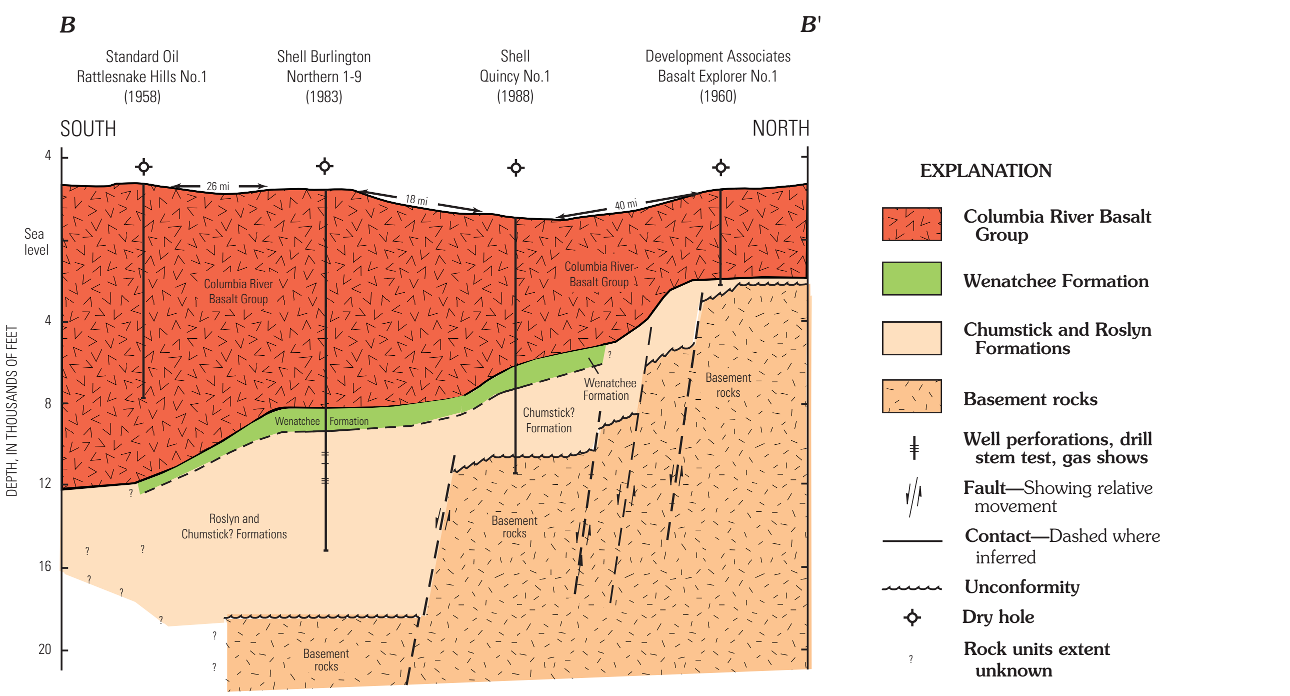

Figure 31. Interpretive south to north cross section portraying the Columbia Basin in central Washington as a rift-graben structure, with faulted pre-Tertiary basement rocks overlain by Paleocene to Oligocene, largely sedimentary strata, and by the Miocene Columbia River Basalt Group. Not to scale. See figure 6 for location of cross section. Stratigraphic contacts in wells modified from Campbell and Banning (1985), Tennyson and Parrish (1987), Campbell (1989), and Wilson and others (this volume). Cross section modified from Wilson and others (this volume).

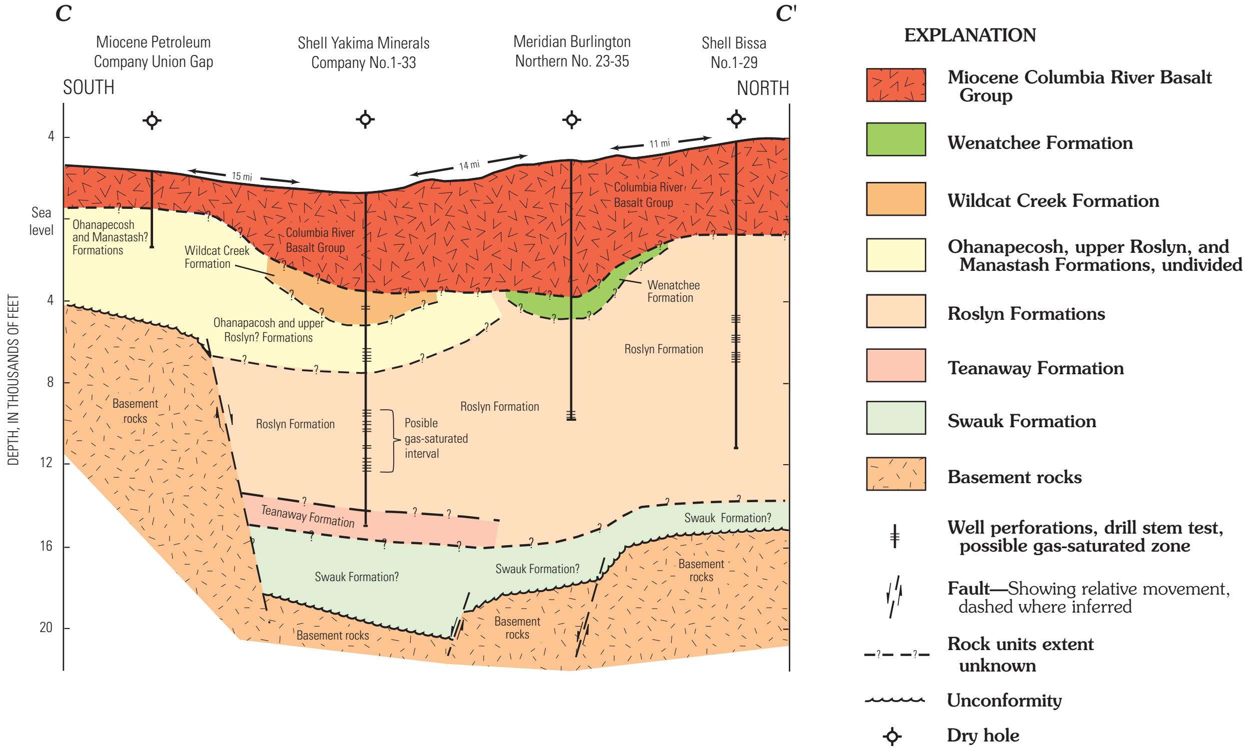

Figure 32. Interpretive south to north cross section portraying the Columbia Basin in central Washington as a rift-graben structure, with faulted pre-Tertiary basement rocks overlain by Paleocene to Oligocene, largely sedimentary strata, and by the Miocene Columbia River Basalt Group. Not to scale. See figure 6 for location of cross section. Stratigraphic contacts in wells modified from Campbell and Banning (1985), Tennyson and Parrish (1987), Campbell (1989), Campbell and Reidel (1994), and Wilson and others (this volume). Cross section modified from Wilson and others (this volume).

show probable graben structures with relative fault movement below the basalt. Well perforations, gas-saturated zones, and drill-stem tests are also shown if data were available. The cross sections depict the Columbia Basin of central Washington as a rift-graben structure.

Modeling of burial history, thermal maturity, and timing of petroleum generation by Tennyson and Parrish (1987) for the Shell Yakima Minerals 1-33 exploration well (figs. 20, 30) and the recent modeling for the Shell Burlington Northern 1-9 (figs. 21, 30) indicate that maturation of upper Eocene (Roslyn Formation) source rocks probably began during the Miocene following burial by the Columbia River Basalt. Maturation could have been as early as the Oligocene for the lower Eocene Swauk Formation (fig. 20; Tennyson and Parrish, 1987). Vitrinite reflectance values from coal samples analyzed from the two wells fit the calculated R_o values in the burial history plots (Lingley and Walsh, 1986).

Reservoir rocks in the Washington part of the AU are arkosic fluvial sandstones in the Paleogene Swauk, Chumstick, Roslyn, and Wenatchee Formations. Porosities as much as 13 to 16 percent have been reported (Lingley and Walsh, 1986; Walsh and Lingley, 1991). Zeolitization is widespread in outcrops as well as in drill cuttings of the Eocene rocks, thereby reducing their permeability (Lingley and Walsh, 1986; Tennyson and Parrish, 1987; Wilson and others, this volume). Analyzed drill cuttings in the Shell Burlington Northern 1-9 well revealed zeolites below 13,100 ft, and in the Shell Bissa 1-29 well zeolite cements were encountered below 11,320 ft with no visible porosity (Wilson and others, this volume). Seals are most likely interbedded fluvial shales within the Eocene Roslyn and Chumstick Formations, and possibly altered volcaniclastic rocks and volcanic ash beds.

A “sweet spot” is defined (fig. 33) as an area below the Columbia River Basalt where hypothetical grabens may contain overpressured gas-bearing Eocene to Oligocene rocks with vitrinite reflectance values equal to or greater than 0.7 percent. Depth of this potential gas-bearing zone ranges from 9,800 to more than 17,500 ft (figs. 31, 32). This postulated sweet spot is approximately 56 percent of the AU (about 2,300,000 acres; fig. 33). Vitrinite reflectance data from exploration holes penetrating Eocene strata yielded values of 1.1 percent at 10,810 ft in the Shell Yakima Minerals 1-33 and 1.3 percent at 15,820 ft in the Shell Burlington Northern 1-9 (Lingley and Walsh, 1986). Both of these wells contain R_o values exceeding the threshold of 0.7 percent, as well as the threshold of 0.75 to 1.0 percent suggested for unconventional gas accumulations (Spencer, 1989; Law and Spencer, 1993; Law, 1996; Law 2002). Overpressured gas was tested in the Shell Burlington Northern 1-9 well: 2.4 million cubic of gas per day (MMCFD) with moderate water flow rates (134 barrels of water per day, BWPD) at 12,694 to 12,699 ft and 3.1 MMCFD with low water flow rates at 13,372 to 13,388 ft.

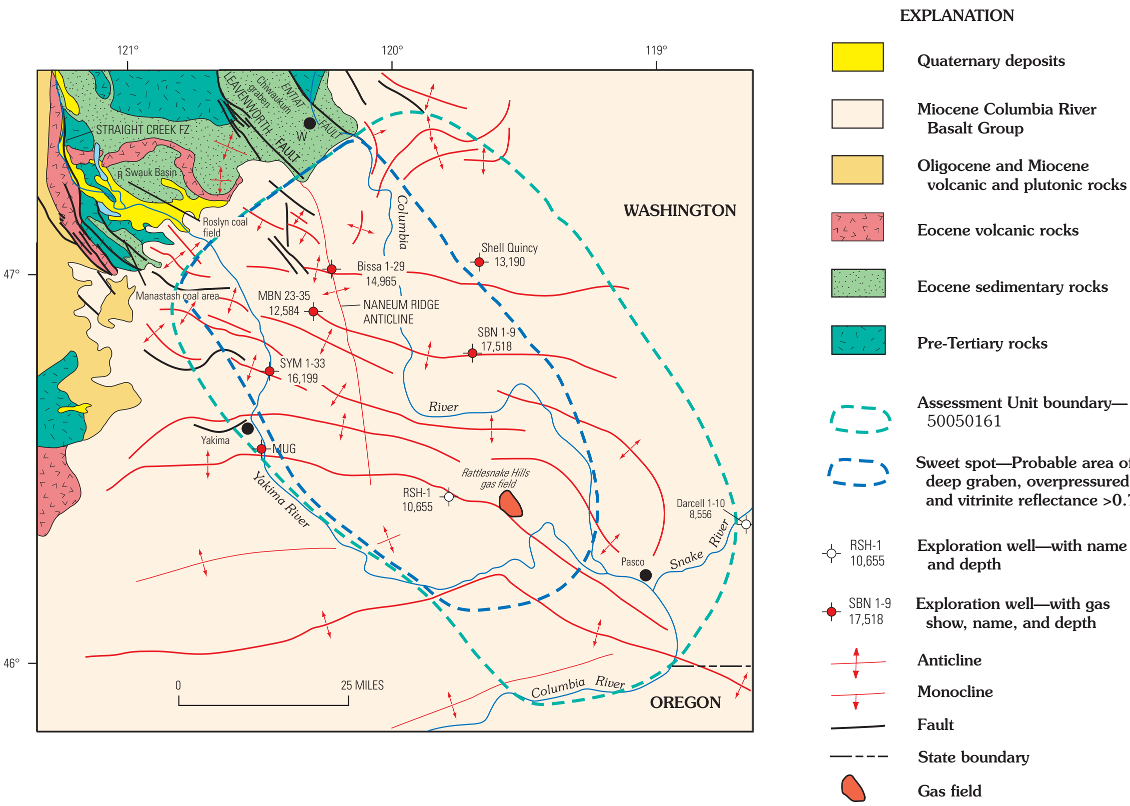

Figure 33. Generalized geology of the Columbia Basin showing outlines of the Columbia Basin Continuous Gas Assessment Unit (50050161) and the sweet spot defined as the overpressured gas-bearing interval below the Columbia River Basalt Group with vitrinite values greater than 0.7 percent. Also shown are geologic units, exploration wells, faults, fold axes, Roslyn coal field, and the Manastash coal area. The Yakima fold belt is generally located north and west of the Yakima River within CRBG. Darcell 1-10, Shell Darcell No. 1-10; FZ, Fault zone; R, Roslyn; SQ-1, Shell Quincy No. 1; SBN 1-9, Shell Burlington Northern 1-9; RSH-1, Standard Oil Rattlesnake Hills No. 1; MUG, Miocene Union Gap; SYM 1-33, Shell Yakima Minerals Company 1-33; MBN 23-35, Meridian Burlington Northern 23-35; Bissa 1-29, Shell Bissa 1-29; W, Wenatchee. Geology modified from Johnson and others (1993), and Campbell (1989).

A plot was constructed showing shut-in pressures in pounds per square inch (PSI) with the hydrostatic gradient (fig. 34) and two overpressured gradients. Mud weights were converted to PSI and then compared with the three reported shut-in pressures measured during drill-stem tests; the data indicate a zone of overpressured gas below the 9,800 ft threshold for the AU. One other well reported a zone of overpressure—the Meridian Burlington Northern 23-35 well tested at 6,700 PSI at a depth of 11,372 ft, which is higher than the hydrostatic gradient. Bottom-hole temperatures measured from wells that penetrated the postulated overpressured gas zone range from 230° to 362°F (Wilson and others, this volume), exceeding the threshold for continuous gas (Law and Dickinson, 1985; Spencer, 1989; Law, 2002 Wilson and others, this volume). Several other exploration wells had gas shows (fig. 29).

Because of the lack of well production data in this AU, the Rock Springs–Ericson Continuous Gas Assessment Unit (AU 50370562) in southwest Wyoming (Johnson and others, 2005) was used as an analog to estimate total recovery for untested cells having potential for additions to reserves over the next 30 yr. Both AU have produced gas from lenticular sandstones interbedded with coals and carbonaceous shales.

The geologic probability of the Columbia Basin Continuous Gas AU is 1.0, because evidence exists for adequate petroleum charge, reservoirs, traps, and seals, and favorable geologic timing for an untested cell to contain at least the selected minimum of 0.02 BCFG (Appendix B). The estimated minimum, mode, and maximum of the total area of the AU are 3,669,000, 4,077,000, and 4,484,000 acres, respectively (Appendix B). The estimated minimum, median, and maximum areas of the AU that is untested are 100, 100, and 100, respectively (Appendix B).

The estimated minimum, mode, maximum, and calculated mean percentages of untested area within the AU that has potential for additions to reserves in the next 30 years is 5, 20, 40, and 22 percent, respectively (Appendix B). A necessary condition is that the total recovery per cell is equal to or greater than the minimum recovery per cell of 0.02 BCFG, and it is likely that this minimum amount of gas can be recovered from a majority of the untested cells in the AU. As previously discussed, the AU contains a thick sedimentary section containing continuous gas and reservoir rocks that were deposited in depositional settings similar to the analog Rock Springs–Erickson Continuous Gas AU (Johnson and others, 2005).

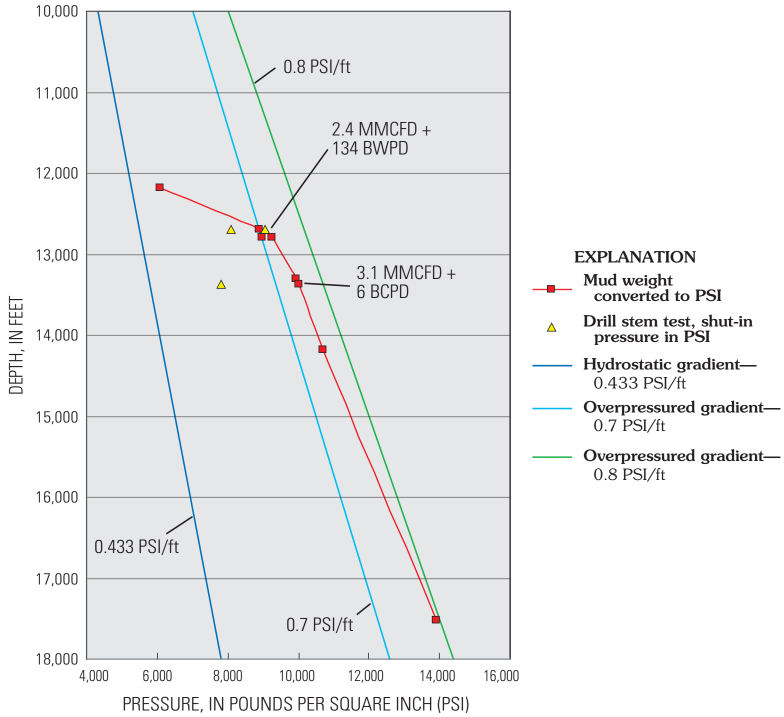

Figure 34. Plot showing shut-in pressure data in pounds per square inch (PSI) from the Shell Burlington Northern 1-9 exploration well, the converted mud weights in PSI, the hydrostatic gradient, and two overpressured gradients in the Columbia Basin Continuous Gas Assessment Unit (50050161). BCPD, Barrels of condensate per day; BWPD, Barrels of water per day, MMCFD, Million cubic feet of gas per day. See figures 6 and 29 for well location.

The minimum, median, and maximum total recovery for untested cells having potential for additions to reserves in the next 30 yr are 0.02, 0.2, and 3 BCFG, respectively (Appendix B). These values were modified from similar values used in the analog AU. The median value of 0.2 BCFG was less than the median value of 0.4 for the analog AU (Johnson and others, 2005) because of the lack of producing wells. These estimates for the total recovery for untested cells, however, assume that the future production for the Columbia Basin Continuous Gas AU would be significantly greater in the next 30 yr.

The USGS assessed mean undiscovered volumes in the Columbia Basin Continuous Gas AU of 2,122 billion cubic feet (BCF) of unconventional (continuous) gas (table 1) and 9.2 million barrels of natural gas liquids (MMBNGL). The estimated mean size of the largest gas field is 103.8 BCF. The estimated mean 2,122 BCF of continuous gas (87 percent) of the total estimated mean total of 2,427 BCF of gas within the Cretaceous-Tertiary Composite TPS is presumed to be trapped in Tertiary rocks overlain by the Columbia River Basalt Group.

Republic Graben Gas Assessment Unit (50050102)

A sequence of probable hydrocarbon-generating sedimentary and volcaniclastic Tertiary rocks were described in the Republic graben by Gaylord (1989) and Gaylord and others (1987, 1996). The graben, located in the northeastern part of the Eastern Oregon and Washington Province (fig. 35), contains at least 9,800 ft of basin fill, including the Eocene O’Brien Creek Formation, Sanpoil Volcanics, and the Klondike Mountain Formation (fig. 36). The lower part of the Klondike Mountain Formation (fig. 37) contains organic-rich rocks consisting of thick, fossiliferous, rapidly deposited fluvial and deltaic rocks, with minor lacustrine rocks, which are locally coal bearing, interbedded with volcanic and volcaniclastic rocks (Gaylord, 1989; Gaylord and others, 1987, 1996), The formation is at least 2,950 ft thick in the Republic graben (Gaylord and others, 1987, 1996) and as much as 8,200 ft thick in the Toroda Creek graben (Suydam and Gaylord, 1997; Morris and others, 2000). The lower part of the Klondike Formation (fig. 37) contains 980 to 1,300 ft of organic-rich rocks with TOC values ranging from 1 to 4 percent (Gaylord and others, 1987). However, because of (1) uncertainty about the presence of suitable reservoir rocks, (2) difficulty in correlating sedimentary units with the graben because of intragraben faulting, and (3) lack of detailed data on hydrocarbon generating rocks, the Republic Graben Gas AU was not assessed.

Summary

The U.S. Geological Survey recently completed an assessment of the undiscovered gas resources of the Eastern Oregon and Washington Province; which includes an area of about 60,000 mi^2. Within the province, estimated mean totals are 2,427 billion cubic feet of gas (BCFG) and 9.81 million barrels of natural gas liquids. About 87 percent of the gas (2,122 BCFG) is contained within the hypothetical Columbia

Figure 35. Areas of the Eastern Oregon and Washington Province (red outline) in north-central and northeastern Oregon and eastern Washington, Cretaceous-Tertiary Total Petroleum System (blue outline), and Republic Graben Gas Assessment Unit (50050102; orange outline), and the location of Rattlesnake Hills gas field. Assessment unit (50050102) was not quantitatively assessed.

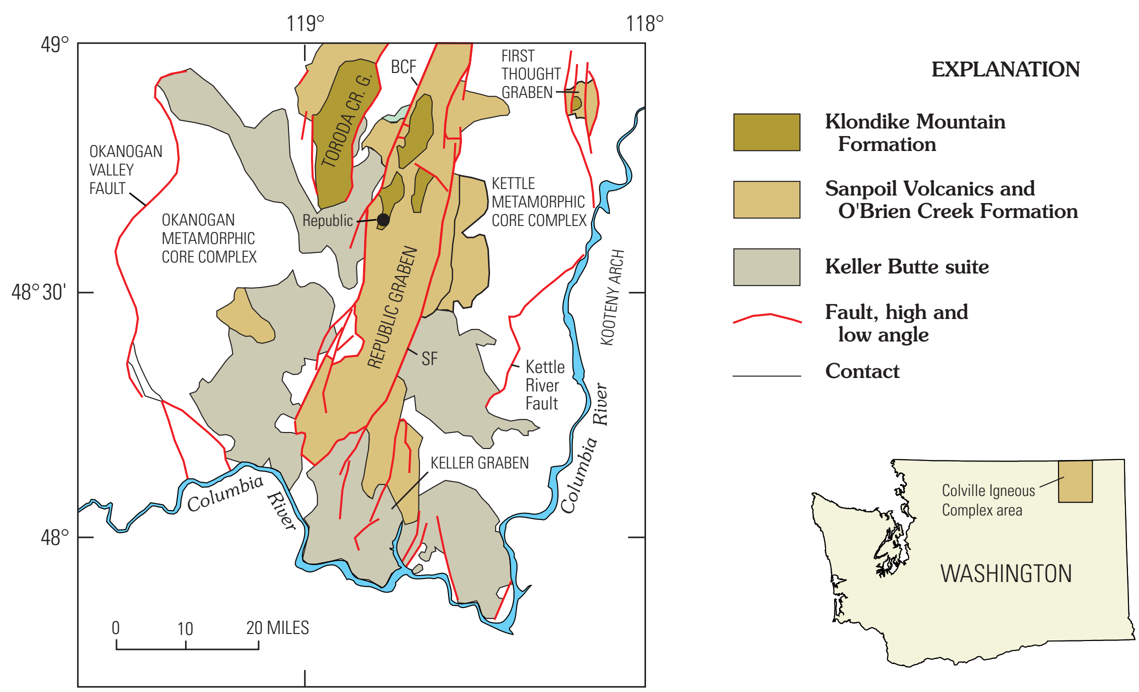

Figure 36. Generalized geology of the Colville Igneous Complex, showing the Republic, Toroda Creek, Keller, and First Thought grabens, major high- and low-angle faults, and Tertiary sedimentary and volcanic units. The Okanogan and Kettle metamorphic core complexes are predominantly pre-Cretaceous gneisses. Area south of the Columbia River is covered by the Columbia River Basalt Group. BCF, Bacon Creek fault; Cr., Creek, G., graben, SF, Sherman fault; Modified from Morris and others (2000).

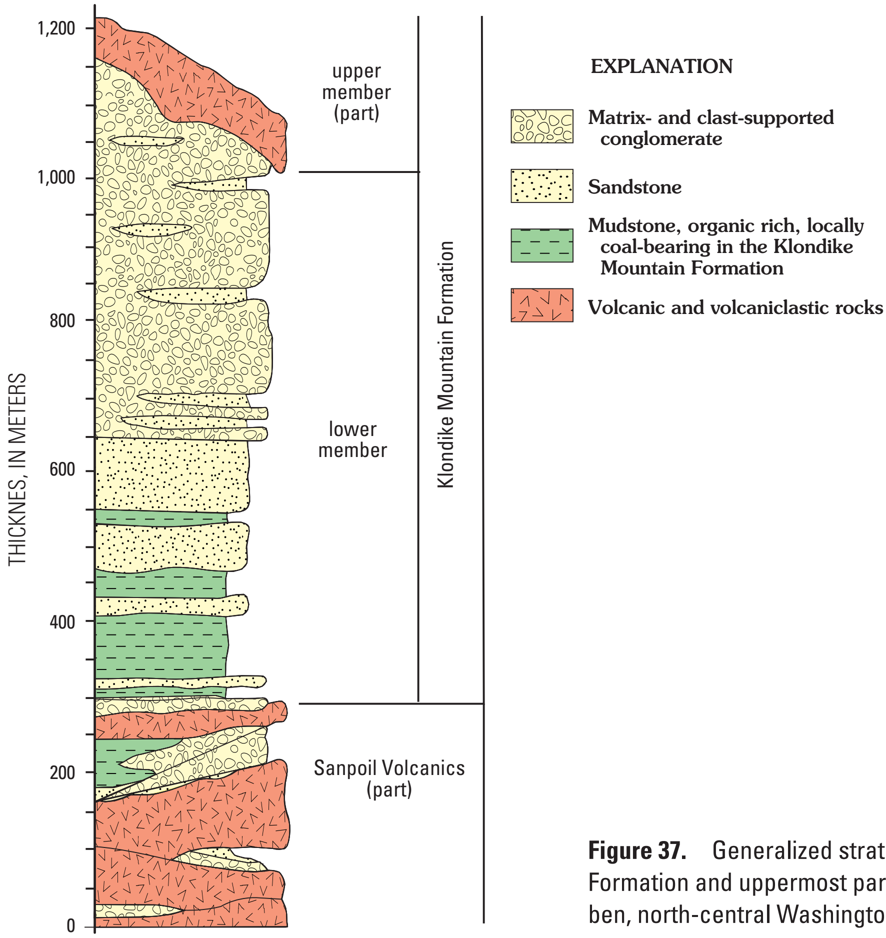

Figure 37. Generalized stratigraphic column showing the Klondike Mountain Formation and uppermost part of the Sanpoil Volcanics in the Republic graben, north-central Washington. Modified after Gaylord and others (1996).

Basin Continuous Gas AU, which encompasses an area of more than 4 million acres. The estimated mean size of the largest gas field is 103.8 billion cubic (BCF) of continuous gas. An estimated 305 BCF of conventional gas is present in the hypothetical Eastern Oregon and Washington Conventional Gas AU, which contains more than 22.2 million acres. The estimated mean size of the largest gas field is 78.3 BCF of conventional gas.

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Laura Roberts modeled the burial history and thermal maturity for the Shell Burlington Northern 1-9 exploration well, and Philip Nelson supplied digital logs and interpretation of well pressure data. The author thanks Lorna Carter, William Keefer, Douglas Nichols, Christopher Schenk, and Marilyn Tennyson for their suggestions, comments, and editorial reviews, which greatly improved the manuscript.

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Appendix A. Input parameters for the Eastern Oregon and Washington Conventional Gas Assessment Unit (50050101), Cretaceous-Tertiary Composite Total Petroleum System, Eastern Oregon and Washington Province.

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

IDENTIFICATION INFORMATION

Assessment Geologist	Michael E. Brownfield and Marilyn E. Tennyson	Date:	
Region:	North America	Number:	2
Province:	Eastern Oregon and Washington	Number:	5005
Total Petroleum System	Cretaceous-Tertiary Composite TPS	Number:	500501
Assessment Unit:	Eastern Oregon and Washington Conventional Gas	Number:	50050101
Based on Data as of:			
Notes from Assessor:	This hypothetical gas assessment unit is defined over a large area where potential reservoir and source rocks are known or inferred to coexist, although thick volcanic sequences obscure the reservoir and source rock intervals.		

CHARACTERISTICS OF ASSESSMENT UNIT

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

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

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

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

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. > minimum size:	**1.0**
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. > minimum size:	**0.8**
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. > minimum size:	**1**

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): **0.8**

UNDISCOVERED ACCUMULATIONS

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

	minimum (>0)	mode	maximum
Oil Accumulations:	NA	NA	NA
Gas Accumulations:	**1**	**5**	**50**

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

	minimum	median	maximum
Oil in Oil Accumulation	NA	NA	NA
Gas in Gas Accumulat	**3**	**10**	**500**

Appendix A. Input parameters for the Eastern Oregon and Washington Conventional Gas Assessment Unit (50050101), Cretaceous-Tertiary Composite Total Petroleum System, Eastern Oregon and Washington Province.—Continued

AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

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

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

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS
(variations in the properties of undiscovered accumulations)

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

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

Gas Accumulations:	minimum	mode	maximum
Inert gas content (%)	0.1	5.8	7
CO_2 content (%)	0	0.2	5
Hydrogen-sulfide content (%)	0	0	0.01
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	600		2,600		5,250

Appendix B. Input parameters for the Columbia Basin Continuous Gas Assessment Unit (50050161), Cretaceous-Tertiary Composite Total Petroleum System, Eastern Oregon and Washington Province.

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

IDENTIFICATION INFORMATION

Assessment Geologist:	M.E. Brownfield and M.E. Tennyson	Date:	
Region:	Pacific Coast	Number:	2
Province:	Eastern Oregon and Washington	Number:	5005
Total Petroleum System:	Cretaceous-Tertiary Composite TPS	Number:	500501
Assessment Unit:	Columbia Basin Continuous Gas AU	Number:	50050161
Based on Data as of:	PI data as of 2005		

Notes from Assessor: Analog—Rock Springs-Ericson Continuous Gas (AU 50370562), Southwest Wyoming Province, used for success ratios and EURs

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CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additior **Gas**

What is the minimum total recovery per cell? 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)

Number of tested cells: **6?** One well with 2 gas zones, 2.4 and 3.1 mmcfgd respectively

Number of tested cells with total recovery per cell ≥ minimum: **0**

Established (discovered cells): ______ Hypothetical (no cells): **X**

Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)

1st 3rd discovered ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

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

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

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

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

   calculated mean ______ minimum 3,669,000 mode 4,077,000 maximum 4,484,000

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

   calculated mean 120 minimum 40 mode 120 maximum 200

   values from the Wind River assessment where used as possible analogs

   uncertainty of mean: minimum 80 maximum 160

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

   calculated mean 100 minimum 100 mode 100 maximum 100

Appendix B. Input parameters for the Columbia Basin Continuous Gas Assessment Unit (50050161), Cretaceous-Tertiary Composite Total Petroleum System, Eastern Oregon and Washington Province.—Continued

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

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

calculated mean	minimum	mode	maximum
22	5	20	40

Geologic evidence for estimates:

There exists a gas-bearing zone below the Columbia River Basalt that contains over pressured gas and vitrinite values greater than 0.7 percent. Depth of this gas-bearing zone ranges from 9,800 to more than 17,500 feet. This sweet spot is approximately equal to 56 percent of AU or about 2,299,000 acres.

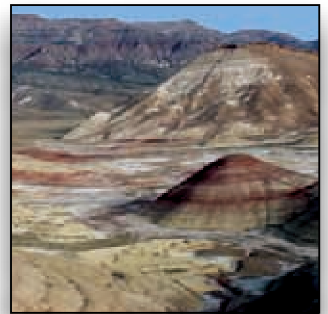
TOTAL RECOVERY PER CELL

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

calculated mean	minimum	median	maximum
	0.02	0.2	3

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

	minimum	mode	maximum
Oil assessment unit:			
Gas/oil ratio (cfg/bo)	NA	NA	NA
NGL/gas ratio (bngl/mmcfg)	NA	NA	NA
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	3	10



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