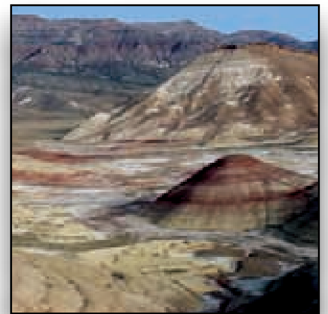
Chapter 4

Evaluation of Well-Test Results and the Potential for Basin-Center Gas in the Columbia Basin, Central Washington



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Volume Title Page

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Chapter 4 of
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By U.S. Geological Survey Eastern Oregon and Washington Province Assessment Team

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Abstract

Lower Tertiary fluvial and volcanic rocks have been recognized beneath the Miocene-age Columbia River Basalt Group in the Columbia Basin in south-central Washington. The U.S. Geological Survey has identified the potential for continuous basin-center gas accumulations in this little-explored basin, based on analyses of geologic and production data from the few deep oil and gas wells that have been drilled as of 2004.

Abnormal pressure gradients, thermally mature source rocks, high reservoir temperatures, natural gas shows, and low-permeability sandstone reservoirs all support the presence of basin-center gas. However, the results of available formation tests conducted in several deep exploration wells indicate that water-bearing zones have commonly been encountered during drilling. An 1,800-foot-thick section of the Eocene Roslyn Formation was penetrated in one of the wells that might be gas saturated. Other test data indicate widespread gas-rich formation water and several zones that produced water at rates of more than 50 barrels per day. Extensive water saturation indicates the probable presence of conventionally trapped gas accumulations. The large volumes of produced water from some intervals indicate that the volume of gas expelled from source rocks may have been inadequate to effectively displace much of the water in potential reservoirs.

Introduction

The U.S. Geological Survey (USGS) is reevaluating the potential for continuous basin-center gas accumulations in selected basins in the United States in order to accommodate changing geologic perceptions since completion of the 1995 National Assessment of United States Oil and Gas Resources (Gautier and others, 1996). The purpose of this effort, which is partly funded by the U.S. Department of Energy, is to identify potential new basin-center gas-assessment units and petroleum systems. The Columbia Basin, occupying about 77,000 mi^2 in central and southern Washington and northern Oregon (fig. 1), was studied for this purpose.

The boundaries and internal structure of the Columbia Basin are poorly known because the sedimentary section is almost entirely covered by thick basalt flows of the Columbia River Basalt Group (figs. 1, 2), and few deep wells have penetrated the sub-basalt sedimentary sequence. However, the data from these wells help to define some important aspects of the geologic relations of potential petroleum plays in the sub-basalt sequence.

As part of the USGS 1995 National Assessment of United States Oil and Gas Resources, Law (1996) identified one continuous basin-center gas play and two conventional gas plays in Tertiary sedimentary rocks beneath the Miocene Columbia River Basalt Group in the Columbia Basin. In this report, we evaluate new data on reservoir properties, gas and water recoveries, gas-production rates, and gas/water contacts in Tertiary sandstone reservoirs that have become available. Data related to the presence (or absence) of continuous basin-center gas are summarized, but no attempt is made to identify new assessment units and petroleum systems or to quantitatively assess gas resources.

Data Sources

Our interpretations and conclusions are based on published data, discussions with industry personnel, and geologic and engineering information accessible in a publicly available database from IHS Energy Group (PI/Dwights PLUS on CD–ROM). The PI/Dwights PLUS data, principally the results of drill-stem and production tests reported for individual wells, are current through February 2000. Because well-completion records depend on information provided by operators, well data in PI/Dwights PLUS may be incomplete.

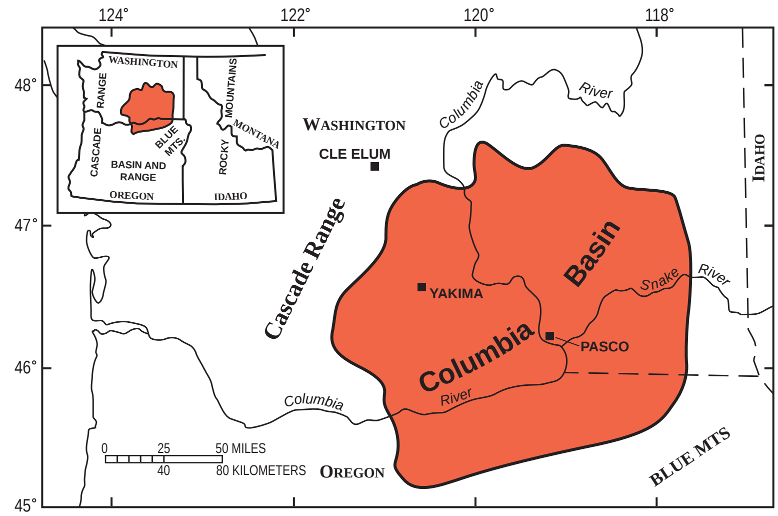

Figure 1. Northern portion of the Columbia Basin of south-central Washington and northern Oregon. The shaded area represents that portion of the basin with significant thickness (greater than 3,000 feet) of early to middle Tertiary sedimentary rocks below the Columbia River Basalt Group (Campbell, 1989, p. 217). The total area overlain by the Columbia River Basalt group is much greater in extent.

	PERIOD/ EPOCH	AGE Ma	STRATIGRAPHIC UNIT		LITHOLOGY
TERTIARY	PLEISTOCENE		Hanford		
TERTIARY	PLIOCENE	3.3	Ringold		
TERTIARY	MIOCENE	8.5 13.5	Columbia River Basalt Group	Saddle Mountains Basalt	Basalt and tuff
TERTIARY	MIOCENE	14.5	Columbia River Basalt Group	Wanapum Basalt	Basalt and tuff
TERTIARY	MIOCENE	15.6	Columbia River Basalt Group	Grande Ronde Basalt	Basalt and tuff
TERTIARY	MIOCENE	17.5	Columbia River Basalt Group	Imnaha Basalt	Basalt and tuff
TERTIARY	OLIGOCENE	30	Wildcat Creek Wenatchee Ohanapecosh		Rhyolite and basalt flows interbedded with tuff and sandstone
TERTIARY	EOCENE	40	Naches		Rhyolite and basalt flows interbedded with tuff and sandstone
TERTIARY	EOCENE	47	Roslyn		Arkosic and tuffaceous sandstone, siltstone, shale, coal, and conglomerate
TERTIARY	EOCENE	48	Teanaway		Basalt flows and tuff
TERTIARY	EOCENE	54	Swauk		Lacustrine black shale,limestone, arkosic sandstone, conglomerate
TERTIARY	PALEOCENE	55	Stuart batholith		Granodiorite and quartz diorite
CRETACEOUS		63 93 138	Stuart batholith		Granodiorite and quartz diorite
JURASSIC		150 205	Ingalls metamorphic rocks		Schist, amphibolite, gneiss, serpentine

Figure 2. Stratigraphic units in the Columbia Basin, south-central Washington. Modified after Campbell (1989, p. 212) and Johnson and others (1993, p. 1195). Ma, millions of years before present.

Acknowledgments

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Regional Geology

The Columbia Basin is covered by volcanic rocks of the Miocene Columbia River Basalt Group (figs. 1, 2). The basin is bordered on the west by the Cascade Range, on the south by the Blue Mountains and Basin and Range Province, and on the north and east by the Rocky Mountains (Reidel and others, 1992). North of the basin, Jurassic and Cretaceous metamorphic rocks, including ophiolites and igneous intrusive rocks, form the regional basement sequence. Lower Tertiary fluvial and volcanic rocks overlie the basement north of the Columbia River and east of the Cascade Range (Johnson, 1985; Tabor and others, 1982) and form a series of complex structural blocks that extend southward into the central part of the Columbia Basin (Campbell, 1989). That portion of the basin located along the Columbia River near the cities of Pasco and Yakima in central eastern Washington (shaded area in fig. 1), which also has been called the Pasco Basin (Campbell, 1989), underwent the most subsidence during the Miocene to Holocene (Campbell, 1989; Johnson and others, 1993).

Davis and others (1978) and Fritts and Fisk (1985a, 1985b) used an extensional model to explain the presence of several Late Cretaceous and early Tertiary fault-bounded grabens and half-grabens (fig. 3) under the Columbia River Basalt Group in south-central Washington and northern Oregon. These depocenters subsequently filled with marine, lacustrine, and fluvial sediments. The stratigraphic sequence (fig. 2) includes (1) a Jurassic, Cretaceous, and Paleocene igneous and metamorphic basement complex overlain by Eocene sedimentary rocks (Swauk Formation); (2) fluvial sandstone and coals of the Eocene Roslyn Formation; and (3) volcanic flows, tuff beds, and arkosic sandstones of the Eocene and Oligocene Naches Formation, and Oligocene Ohanapecosh, Wenatchee, and Wildcat Creek Formations. The pre-Tertiary and lower to middle Tertiary strata are covered by thick volcanic rocks of the Miocene-Pliocene (17.2 to 6 Ma) Columbia River Basalt Group (Campbell, 1989; Johnson and others, 1993; Baksi, 1989). Volcanic rocks and sedimentary interbeds of the Columbia River Basalt Group attain a thickness of more than 10,000 ft in the central part of the Columbia Basin.

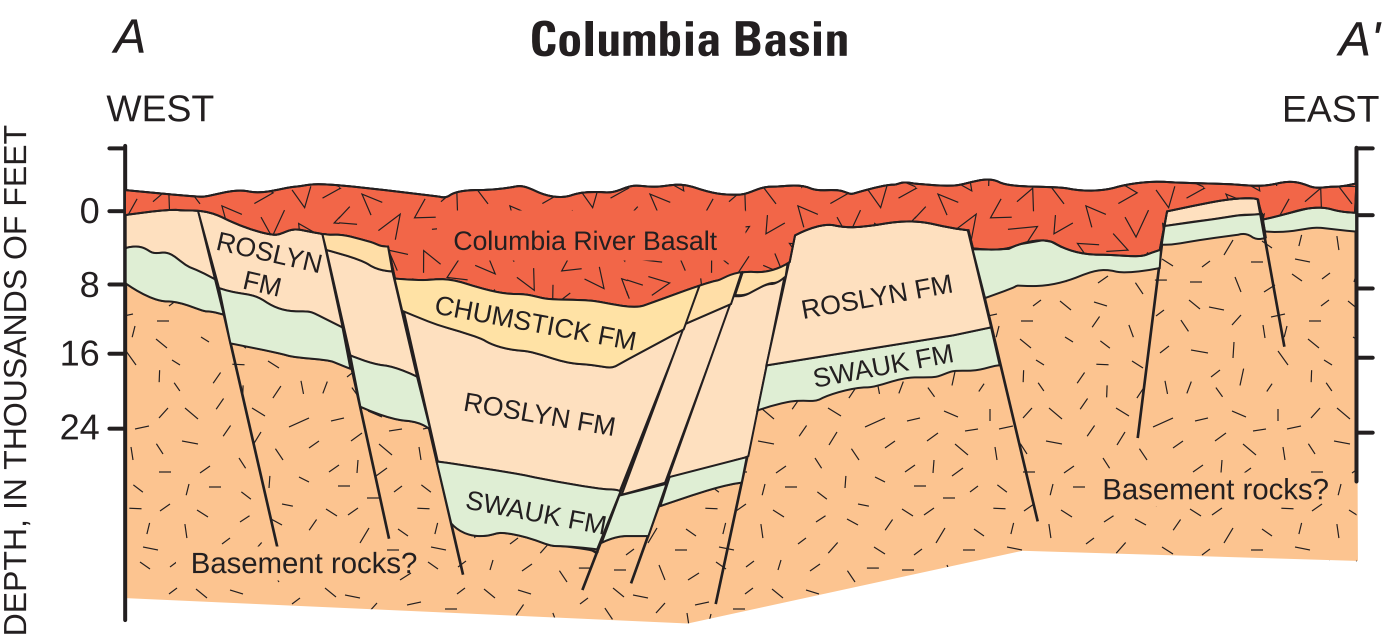

Figure 3. Generalized west-east cross section A–A′ showing an interpretation of the Columbia Basin as a rift graben structure. Not to scale. Modified from Fritts and Fisk (1985b, p. 87).

Sumner and Verosub (1992) suggested that a regional hydrothermal event occurred at approximately 24 to 23 Ma, pre-dating deposition of the Columbia River Basalt Group. Widespread low-temperature hydrothermal activity may have caused extensive chlorite, zeolite, and silica alteration in Cretaceous and Tertiary sedimentary rocks and accelerated the thermal maturation of Tertiary source rocks. Sample descriptions noted in mudlogs of several deep exploratory wells indicate that zeolites (especially laumontite), silica, and chlorite are widespread throughout the sedimentary section. An episode of regional compression beginning in late Miocene and continuing to the present resulted in extensive folding and faulting of the basalt sequence. Maps showing surface anticlines, synclines, and faults have been published by Tolan and Reidel (1989), Campbell (1989), and Johnson and others (1993).

Continuous Gas Accumulations

For the purpose of evaluating gas-resource potential, it is important to distinguish continuous gas accumulations from conventional gas accumulations because of differences in resource assessment methodologies between the two types (Gautier and others, 1996). Continuous gas accumulations generally form within an extensive volume of reservoir rock with spatial dimensions equal to or exceeding those of conventional hydrocarbon accumulations. The definition of continuous gas accumulations used here is based on geologic considerations rather than on government regulations defining low-permeability (tight) gas. The Natural Gas Policy Act of 1978 (NGPA) established price ceilings for wellhead sales of natural gas. The Federal Energy Regulatory Commission (FERC) was given authority under the act to establish incentive prices (prices higher than the otherwise applicable price ceilings) for natural gas produced under "conditions as the Commission determines to present extraordinary risks or costs." Among the types of natural gas that the Commission concluded qualified for incentive pricing was tight formation gas (U.S. Court of Appeals for District of Columbia circuit No. 94–1698).

Common geologic and production characteristics of continuous basin-center gas accumulations include (1) their lack of conventional traps or seals, (2) reservoir rocks with low-matrix permeability, (3) presence of abnormal pressures, (4) large in-place volumes of gas, and (5) low recovery factors (Schmoker, 1996; Law, 2002).

Continuous accumulations were treated as a separate category in the USGS 1995 National Petroleum Assessment and were assessed using a specialized methodology (Schmoker, 1996). Continuous accumulations are diverse geologically and fall into several categories including coal-bed gas, biogenic gas, fractured-shale gas, and basin-center gas. Our report focuses on the potential for basin-center gas within Tertiary clastic reservoirs beneath the thick Columbia River Basalt Group of the Columbia Basin in south-central Washington.

Basin-Center Gas Accumulations

From studies of hydrocarbon-productive basins in the Rocky Mountain region, Law and Dickinson (1985) and Spencer (1989) identified characteristics of basin-center gas accumulations that distinguish them from conventional accumulations. Basin-center gas accumulations:

- are geographically large, typically occupying tens to hundreds of square miles in the central, deeper parts of sedimentary basins.
- are in reservoirs with low permeability—generally less than 0.1 millidarcy (mD)—so that gas is inhibited from migrating by buoyancy.
- lack downdip gas/water contacts because gas is not held in place by buoyancy of water; consequently, water production is low or absent, but produced water is not associated with a distinct gas/water contact.
- commonly are in abnormally pressured reservoirs (generally overpressured, but can be underpressured).
- contain primarily thermogenic gas, and, where overpressure is encountered, the overpressuring mechanism is thermal generation of gas.
- are structurally downdip from water-bearing reservoirs that are normally pressured, or in some cases, underpressured.
- lack traditional seals and trapping mechanisms.
- contain gas-prone source rocks proximal to the low-permeability reservoirs; hence, migration distances are short.
- are in settings such that the tops of basin-center gas accumulations fall within a narrow range of thermal maturity, usually between a vitrinite reflectance (R_o) of 0.75 and 0.9 percent.

What Causes a Basin-Center Gas Accumulation to Form?

The most common geologic setting that leads to basin-center gas accumulations involves low-permeability reservoirs near gas-prone source rocks that were buried to depths sufficient for the generation of thermogenic gas. Overpressuring conditions then develop when generation occurs at a rate that exceeds the rate at which gas escapes updip by migration through the low-permeability reservoir. As overpressuring develops, any free water in pores of the low-permeability reservoir is forced out updip into more highly permeable and normally pressured strata; only bound, irreducible water remains (Gies, 1984; Spencer, 1989; Law and Spencer, 1993). Although gas does migrate slowly through the low-permeability gas reservoir, retardation of the upward flow is generally sufficient to maintain overpressured conditions.

In some cases, basin-center gas accumulations can either be normally pressured or underpressured as a result of uplift in a tectonically active basin. Such gas accumulations might have only some of the characteristics for basin-center gas previously described; thus, differentiating between basin-center and conventional accumulations can be difficult and subjective, which we have found to be the case in evaluating the potential for basin-center gas in the Columbia Basin (see “Discussion” section).

Exploration History

Despite the technological problems associated with drilling through thousands of feet of basalt, the Columbia Basin has been the focus of exploration activity by several petroleum companies. Early drilling activity was stimulated by reports of gas in water wells. Gas shows and strong water flows were reported in the Miocene Petroleum Company, Union Gap well (MUG, fig. 4), which was drilled in 1929 to a total depth of 3,811 ft (table 1). Shallow gas production was established in 1930 at the Rattlesnake Hills gas field in Yakima County (fig. 4), where low-pressure gas containing 97 percent methane and 2.5 percent nitrogen was trapped in basalt flows at depths of only 700 to 915 ft in a faulted anticline (Hammer, 1934). The field, which has produced approximately 1.3 billion cubic feet of gas (BCFG) from 16 wells, is considered to be a conventional accumulation in that it has a distinct gas/water contact. The field was abandoned in 1941 (McFarland, 1979).

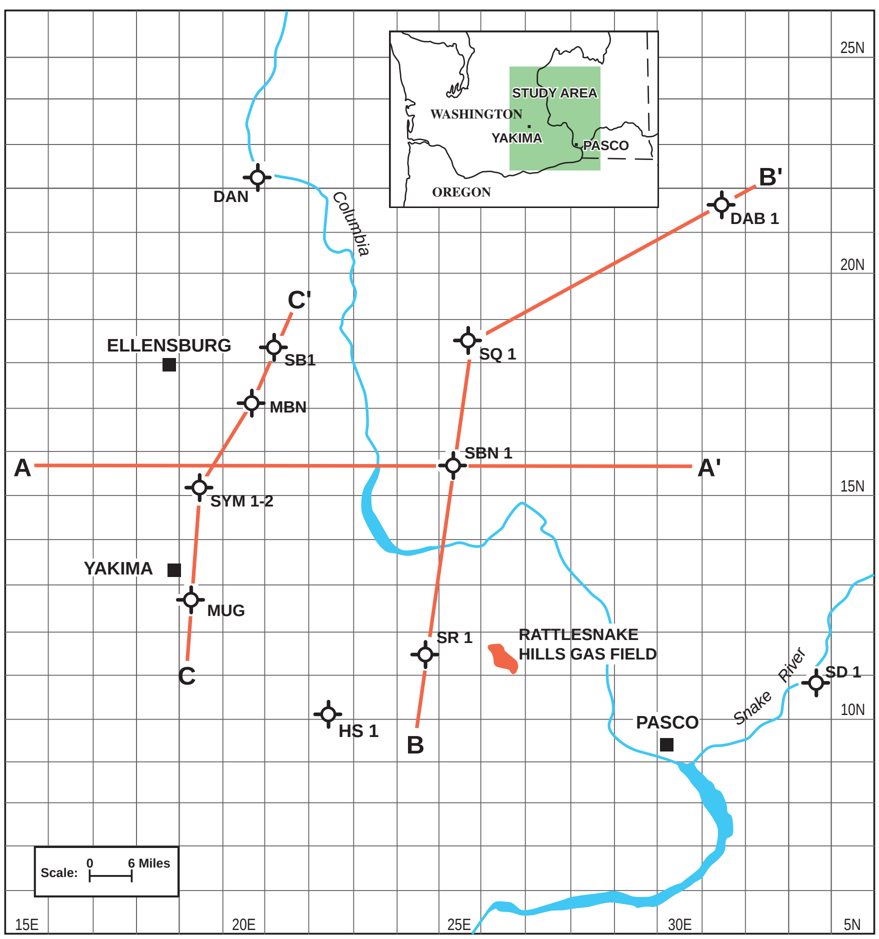

Figure 4. Cities and towns, rivers, locations of key wells in the Columbia Basin, and cross sections referenced in this report. Modified after Johnson and others (1993), and Campbell (1989). SD1, Shell Darcell No. 1; DAB1, Development Associates Basalt Explorer No. 1; SQ1, Shell Quincy No. 1; SBN1, Shell Burlington Northern No. 1; SR1, Standard Oil Rattlesnake Hills No. 1; HS1, P.J. Hunt Snipes No. 1; MUG, Miocene Union Gap; SYM1-2, Shell Yakima Minerals Company No. 1 and No. 2; MBN, Meridian Oil Co. B.N. No. 23; SB1, Shell Bissa No. 1; DAN, Development Associates NORCO No. 1.

Table 1. Well data for key wells in Columbia Basin from IHS Energy Group (petroROM Version 3.43, 2001), Denver Earth Resources Library, 730 17th Street, Denver, CO 80202, and published reports.

[Data include well name and number, well location by section (sec.), township, and range (T.R.), tested formation and depth of test, drilling mud weight (Mud) in pounds per gallon (ppg), bottom hole temperature (BHT) in degrees Fahrenheit, vitrinite reflectance (R_o), shut in pressure in pounds per square inch (psi), pressure gradient in pounds per square inch per foot (psi/ft), permeability in millidarcies (mD), porosity in percent, and comments. Abbreviations in right-hand column: Perfd, perforated depth; Abd., abandoned; rec., recovered; MCFD, thousand cubic feet of gas per day; MMCFD, million cubic feet of gas per day; BWPH, barrels of water per hour; BCPD, barrels of condensate per day; ss, sandstone; sh, shale; ls, limestone; kh, permeability times height of reservoir; SIP, shut in pressure; FSIP, final shut in pressure; Pgrad, pressure gradient; DST, drill-stem test; ppm, parts per million; tr, trace; frac'd, fractured; fm, formation; sec., section; TD, total depth of well; P&A, plugged and abandoned well; >, greater than; BWPD, barrels of water per day; B.N., Burlington Northern.]

Well name	No.	County	Sec.	T.	R.	Strat. unit	Depth (ft)	Mud (ppg)	BHT (degF)	R_o at depth (percent at ft)	SIP (psi)	Pgrad (psi/ft)	Perm (mD)	Porosity (percent)	Test results, cores, comments
Shell Darcell	1-10	Walla	10	10 N.	33 E.	basement	8,556	11.8	158						Base of basalt=7,820 ft. Tuff + Ss. Basement = gneiss at 8,390 ft.
Paul John Hunt Snipes	1	Yakima	33	10 N.	22 E.		1,176								Basalt to 1,079 ft. Green shale to 1,176 ft with gas shows, water flows.
Standard Oil Rattlesnake	1	Benton	15	11 N.	24 E.	basalt	9,495	68.0	230						Deep test at Rattlesnake gas field. TD = 10,650 ft in basalt.
Miocene Petr. Co. Union Gap		Yakima	17	12 N.	19 E.	Swauk (?)	3,810								Basalt to 1,811 ft. Shale + ls to 3811 ft with gas + oil shows, water flows.
Bailey	1	Yakima	24	14 N.	17 E.	basalt	530								TD in basalt. Tested 500 MCFD ? Gas = 69% N_2 + 28% CH_4.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Wildcat Ck	5,800								Perf'd 5,770–5,880 ft, rec 1,030 BWPD + trace of gas. Abd.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Ohanapecosh	7,700								Perf'd 7,535–8,040 ft, rec gas at 27 MCFD + 1700 bwpd. Abd.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Roslyn	10,796		228	1.1 at 10,810					Perf'd 10,604–10,930 ft, rec gas at 10 MCFD. Abd.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Roslyn	11,240			1.2 at 11,020					Perf'd 11,202–11,256 ft, acidized, rec gas at 85 MCFD. Abd.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Roslyn	11,746	15.0	244	1.38 at 11,870					Perf'd 11,598–11,652 ft, acidized, rec gas at 75 MCFD. Abd.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Roslyn	12,400	15.0							Perf'd 12,430–380 ft, acidized, frac'd, rec gas at 150 to 500 MCFD. Abd.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Roslyn	13,968	15.0	314						Perf'd 12,976–13,568 ft, flowed 570 MCFD and 5,400 BWPD. Abd.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Roslyn	15,500	16.0							Perf'd 15,466–15,540 ft, acidized, rec trace of gas, no flow rate. Abd.
Shell Yakima Minerals Co.	1-33	Yakima	33	15 N.	19 E.	Teanaway	15,865	16.0	362						Stuck pipe at 16,199 ft. Top of fish= 15,870 ft.
Shell Yakima Minerals Co.	2-33	Yakima	33	15 N.	19 E.	Wildcat Ck	5,609	13.0	158				400	10–20	Perf'd 5,133–5,174 ft, rec trace of gas. Abd. Basalts + tuff to 5,100 ft.
Shell Yakima Minerals Co.	2-33	Yakima	33	15 N.	19 E.	Wildcat Ck	5,609	13.0	158						Perf'd 5,282–5,322 ft, acidized, rec trace of gas. Abd. Cut 7 cores.
Shell Yakima Minerals Co.	2-33	Yakima	33	15 N.	19 E.	Wildcat Ck	5,609	13.0	158				250	10–15	Perf'd 5,360–5,397 ft, acidized, rec gas at 25–50 MCFD. Abd.
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Wenatchee	12,177	9.6	200	0.6 at 12,000					Basalt to 11,500 ft. Thin ss, sh, coal beds. Gas shows. Cut 9 cores.
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn	12,696	13.5							Perf'd 12,694–12,699 ft, rec gas at 2.4 MMCFD + 134 bwpd[1]
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn	12,792	13.5			8,100	0.64			BHP = 8,100 psi at 12,696 ft (0.64 psi/ft) before fracturing stimulation.
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn	12,700	13.5			9,065	0.72			DST at 12,792 ft, FSIP=9,065 psi (0.72 psi/ft), rec not recorded
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn	12,800	13.9							Perf'd 12,694–12,880 ft, rec 553 MCFD gas. Frac'd 12,880-12,694 ft, rec
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn									2,395 MCFD & 5 BWPH. Prefrac kh=1.33 mDft, postfrac kh=2.02 mDft.
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn	13,300	14.4							Perf'd 13,288–13,304 ft, flowed 5 BWPH. Zeolites below 13,100 ft.
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn	13,380	14.4			7,800	0.58	0.23	5–10	Perf'd 13,372–13,388 ft, rec 350 MCFD + 9 BWPD. Frac'd, rec 3,100 MCFD
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn									+ 6 BCPD. Pre-frac kh= 3.8 mDft, post-frac kh= 7.1 mDft. CO_2 + H_2S.
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn	14,190	14.5		1.1 at 15,120					Perf'd 14,052–14,340', no flow, acidized, swabbed 3 BWPH, tr gas+H_2S.
Shell Burlington Northern	1-9	Grant	9	15 N.	25 E.	Roslyn	17,518	15.3	334	1.3 at 15,820					TD= 17,518 ft in ss and tuff with chlorite + zeolite matrix.
Meridian B.N.	23-35	Kittitas	35	17 N.	20 E.	Wenatchee	8,925	10.6	131						Basalt to 6,680 ft., tuff to 7,860 ft. Roslyn Fm, ss, coal, and tuff to TD.
Meridian B.N.	23-35	Kittitas	35	17 N.	20 E.	Roslyn	11,372	12.3	194		>6,700	>0.55			DST 11,919–12,584 ft., rec cushion, 3,600 ft fm water with 500 ppm Cl-.
Meridian B.N.	23-35	Kittitas	35	17 N.	20 E.	Roslyn	12,584	12.4	240						Stuck DST tool, left fish in hole. Abd.
Shell Bissa	1-29	Kittitas	29	18 N.	21 E.	Roslyn	8,393	9.2	175	0.53 at 9,220					Basalt to 4,580 ft. Perf'd 8,486-8,800 ft, rec trace of gas. Abd.
Shell Bissa	1-29	Kittitas	29	18 N.	21 E.	Roslyn	9,763	9.5	158						Perf'd 9,436–9,830 ft, rec trace of gas. Abd.
Shell Bissa	1-29	Kittitas	29	18 N.	21 E.	Roslyn	10,978	10.3	174	0.57 at 10,080					Perf'd 10,314–10,898 ft, acidized, rec trace of gas. Abd.
Shell Bissa	1-29	Kittitas	29	18 N.	21 E.	Roslyn	12,324	12.7	220						Heavy laumontite, zeolite cements below 11,320 ft, no visible porosity.
Shell Bissa	1-29	Kittitas	29	18 N.	21 E.	Swauk	13,510	14.6	218						Gas show at 13,560 ft, oil in mud, fluorescence and cut, not tested.
Shell Bissa	1-29	Kittitas	29	18 N.	21 E.	basement	14,965	17.3	270						Swauk Fm, sh, ls, ss below 13,655 ft. Granitic basement at 14,920 ft.
Shell Quincy	1	Grant	22	18 N.	25 E.	Roslyn	11,835	12.5	218						Basalt to 7,200 ft. Ss + tuff to 12,790 ft. Coal bed, gas show at 10,200 ft.
Shell Quincy	1	Grant	22	18 N.	25 E.	basement	13,202	13.9	239						Metamorphic basement at 12,790 ft. No tests reported. Abd.
Dev. Assoc. Basalt Explorer	1	Lincoln	10	21 N.	31 E.	basement	4,682		138						Basalt to 4,465 ft, then ss, sh. Granitic basement at 4,667 ft. Abd.
Dev. Assoc. Norco	1	Chelan	26	22 N.	20 E.	Swauk(?)	4,903			0.5 at 4,850					Drilled in 1935. Several gas shows. Re-entered, logged in 1974. Abd.

[1] Lingley and Walsh 1986

Gas shows and water production were reported in the P.J. Hunt Snipes 1 well (HS1, fig. 4), drilled in 1944 to a total depth of 1,408 ft (table 1). A gas sample from a depth of 1,160 ft contained 66 percent methane, 29 percent nitrogen and 4.5 percent oxygen. Johnson and others (1993) noted that methane gas has been detected in many shallow aquifers in the Columbia River Basalt Group. They suggested that methane gas expelled from thermally mature Eocene coal beds migrated vertically along fault zones into shallow ground-water systems within the basalt flows.

Standard Oil Company drilled an exploratory well to test the deeper potential of the Rattlesnake Hills anticlinal structure in 1958 (SR1, fig. 4). The well reached a total depth of 10,650 ft but bottomed in basalt and tuff without penetrating the underlying sedimentary sequence (Standard Oil Rattlesnake 1, table 1).

Improvements in geophysical prospecting (Campbell, 1981; Halpin and Muncey, 1982) stimulated a second wave of exploratory drilling to evaluate the sedimentary section below the Columbia River Basalt Group. Shell Western Exploration and Production Company completed a drilling program in the Columbia Basin during the 1980s (table 1), and Meridian Oil and Gas Corporation drilled one deep well (Meridian Burlington Northern 23-35) in 1989. All wells were plugged and abandoned without establishing commercial hydrocarbon production.

Although deep commercial production has not yet been established in the basin, the combination of magnetic surveys, regional seismic and gravity data, surface mapping, and deep exploratory drilling have contributed to an improved understanding of the stratigraphy and structure of the sedimentary sequence beneath the basalt. A new phase of drilling may be soon underway and should provide valuable data on deep basin petroleum geology (Oil and Gas Journal, 2005).

Potential for Basin-Center Gas

Tennyson (1996) reviewed exploration activity in the Columbia Basin as part of the 1995 USGS National Assessment of United States Oil and Gas Resources and suggested that a hypothetical basin-center gas play might be present in the Columbia Basin northwest of the Columbia River. Law (1996) noted that (1) many of the characteristics typical of known basin-center gas accumulations were present, including overpressuring, gas shows, and tight-gas sandstones with 6 to 15 percent porosity in the sedimentary section below basalt flows; and (2) gas recovery was at rates of 3.1 million cubic feet of gas per day (MMCFGD) along with “some water” during drill-stem tests in several deep wells.

Evaluation of Well Data

We reviewed data from deep wells in the region (six wells have a total depth exceeding 10,000 ft; see table 1) to evaluate the potential for a basin-center gas accumulation in more detail. Reported drilling-mud weights, bottom-hole temperatures and pressures, vitrinite reflectance, permeabilities, and formation test results are summarized in table 1, and stratigraphic cross sections in figures 5 and 6 illustrate our interpretations of the data from selected key wells.

Bottom-hole temperatures for deep wells ranged from 131° to 362°F (table 1). Most of the temperatures exceed the 190° to 200°F threshold for basin-center gas accumulations proposed by Law and Dickinson (1985) and Law and Spencer (1993). Published vitrinite reflectance (R_o) values (Lingley and Walsh, 1986; Sumner and Verosub, 1987) include 1.1 percent R_o at a depth of 10,810 ft in the Shell Yakima Minerals Co. No. 1-33 well (SYM1–2, fig. 4) and 1.3 percent at a depth of 15,820 ft in the Shell BN No. 1-9 well (SBN1, fig. 4; table 1). Both of these values exceed the threshold of 0.75–1.0 percent R_o suggested by Law (1996), Spencer (1989) and Law and Spencer (1993) for typical basin-center gas accumulations. A lower R_o value (0.57 percent) at a depth of 10,080 ft was measured in the Shell Bissa No. 1-29 well (SB1, fig. 4), which appears to be located on an uplifted fault block (Hog Ranch–Naneum Ridge anticline of Campbell (1989) (cross section C–C’, fig. 6).

Mud logs for several Columbia Basin wells indicate that slight to moderate shows of background gas (mostly methane) were detected throughout much of the sedimentary section. Stronger gas shows with heavier C3, C4, and iC4 hydrocarbons, as well as some solvent cuts, oil stain, and yellow-green oil fluorescence, were detected in several of the deep wells, indicating the presence of condensate and light oil.

Drilling-mud weights and reservoir pressures (table 1) indicate extensive overpressuring within the Roslyn, Teanaway, and Swauk Formations in the central part of the Columbia Basin. Mud weights as high as 16 to 17.3 pounds per gallon (ppg) were used to prevent possible blowouts in deep wells in this area. Reservoir pressures measured during drill-stem and production tests indicate moderate overpressures ranging from 0.55 to 0.72 pounds per square inch per foot (psi/ft). Assuming these measurements to be accurate, the 16 to 17.3 ppg (0.83 to 0.89 psi/ft) drilling muds were significantly overbalanced. Most of the wells were drilled with water-based mud systems, and problems with borehole caving, sloughing, and stuck pipe were reported in several wells. Problems may have occurred with swelling clays in tuff beds when tuff potentially reacted with water in the drilling mud. Unusually high mud weights may have been used to

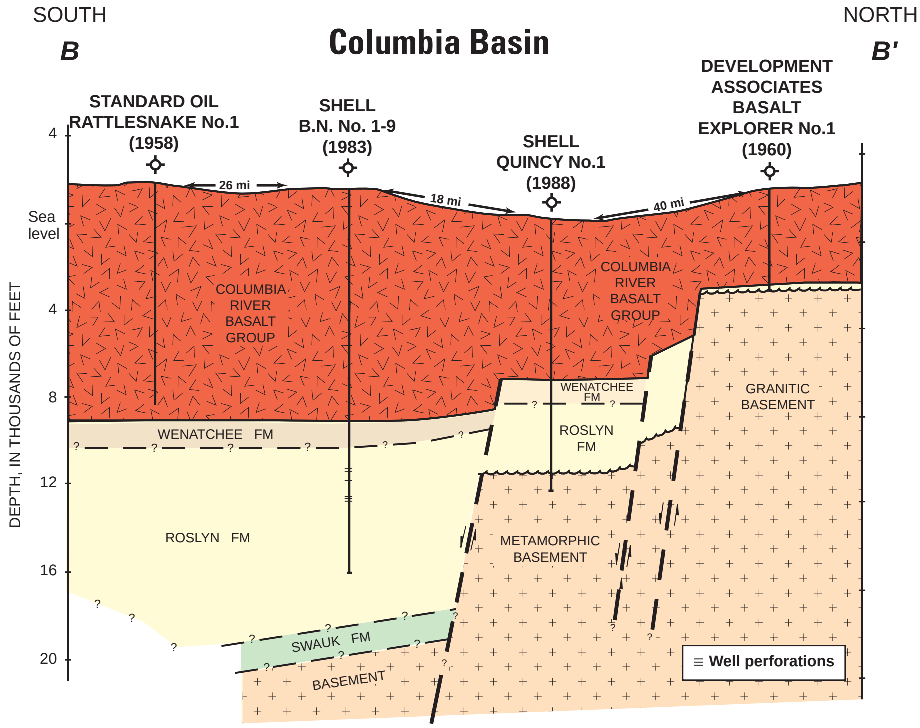

Figure 5. South-north stratigraphic cross section *B–B′* showing hypothetical faults, key wells, and stratigraphic units. Not to scale. See figure 4 for well locations used in cross section. Arrows indicate direction of relative movement. Solid black lines indicate location of faults; dashed where inferred. Scalloped edge where an unconformity exists.

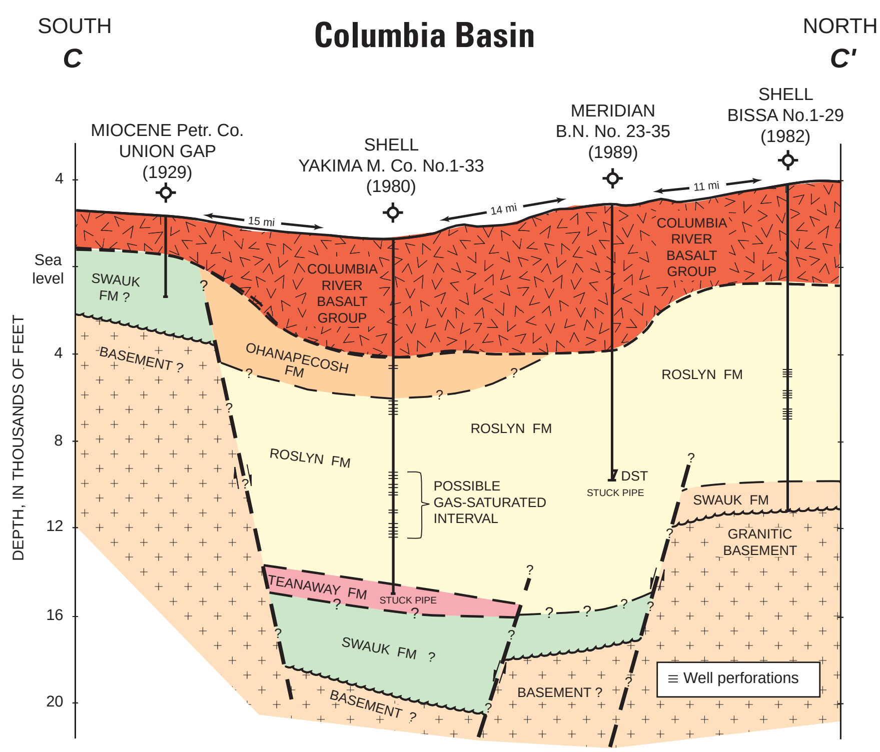

Figure 6. South-north stratigraphic cross section *C–C′* showing hypothetical faults, key wells, and stratigraphic units. Not to scale. See figure 4 for well locations used in cross section. Dashed line indicate location of faults; arrows indicate direction of movement. Scalloped edge where an unconformity exists.

stabilize boreholes that were squeezed because of swelling clays.

Formation test results and shows from wells in the region (summarized in table 1) are available for zones of interest in the Wildcat Creek, Wenatchee, Ohanapecosh, and Roslyn Formations (fig. 2) below the Columbia River Basalt Group. A formation test at depths of 13,372 to 13,388 ft in the Shell BN No. 1-9 well (SBN1, fig. 4), for example, recovered gas and condensate at flow rates of 3,100 MCFD and 6 barrels of condensate per day (BCFD) after hydraulic fracture stimulation. However, the tested interval lies between zones that produced water at high flow rates of 3 to 5 barrels of water per hour (BWPH). Other formation tests resulted in gassy water or water at moderate to high flow rates of more than 50 barrels of water per day (BWPD) (for example, Meridian BN 23-35 at 11,919 ft).

Other tests also resulted in gas and(or) condensate without water (Shell Yakima 2-33 at 5,360 ft; and Shell Yakima 1-33 at 11,598 ft), but the pressuring phase is most commonly water or gassy water rather than only gas. The available test data, though limited and showing mixed results, appear to indicate that the hydrocarbon system contains abundant moveable water. Reservoir rocks appear to have not been extensively dewatered and are not continuously gas saturated.

Hydraulic fracture stimulation was used in many formation tests reported in table 1. At the Shell BN No. 1-9 well (SBN1, fig. 4) a fracture treatment using 7,500 gallons of 15 percent acetic acid in the depth interval 14,052–14,340 ft resulted in water production at 3 BWPH with traces of gas containing 40 to 380 parts per million (ppm) H_2S. This zone was plugged off. As indicated earlier, hydraulic fracture stimulation was also performed in the depth interval 13,372-13,388 ft in this well. Ninety thousand pounds of Interprop was injected, resulting in a shut-in reservoir pressure change from 7,800 psi (0.58 psi/ft) before the treatment to 6,900 psi (0.52 psi/ft) after treatment and a reported increase in gas flow from 350 MCFD to 3,100 MCFD and 2 BCPD. Calculations reported by the operator indicated that the fracture stimulation nearly doubled the “kh” (permeability times height) of the reservoir, which was a thin sandstone layer with good porosity. Farther uphole, perforated intervals at 12,694–12,699 ft produced gas at 553 MCFD with no accompanying water before treatment. After fracture stimulation with 89,000 pounds of Interprop, the “kh” in this interval increased from 1.33 millidarcy-feet (mD-ft) to 2.02 md-ft, and gas and water flowed at stabilized rates of 2,395 MCFD and 5.6 BWPH, respectively. This fracture treatment evidently improved the permeability of the reservoir but also connected a gas-producing zone to a water-producing zone. An acid-fracture stimulation using 77,000 pounds of sintered bauxite proppant at 12,380–12,430 ft in the Shell Yakima Minerals Company No. 1-33 well (SYM1, fig. 4) resulted in a gas flow of 500 MCFD, but the flow rate declined to 150 MCFD within 5 days, and the zone was later plugged.

Hydraulic fracture stimulation of the Roslyn Formation may improve reservoir permeability but may also connect gas-producing zones with nearby water-producing zones. As noted by Johnson and others (1993), the sedimentary section may be crosscut by fault and fracture zones, which can function as permeable pathways for gas and water migrating upward into shallower zones.

Four of the tests conducted at the Shell Yakima Minerals Company No. 1-33 well (SYM1, fig. 4) evaluated zones of interest in the Roslyn Formation. According to reports released by the operator, natural gas flowed at low rates (10 MCFD; 85 MCFD; 75 MCFD; 500 to 150 MCFD) without water production in the 10,604- to 12,430-ft interval. The bottom-hole temperatures ranged from 228 to 244°F in this interval, and published R_o measurements ranged from 1.1 to 1.4 percent, indicating favorable thermal maturity. The thermal maturity data and lack of water production during testing indicate that a gas-saturated section might be present within this 1,800-ft-thick interval. However, zones above and below this interval produced gassy water at high rates (1,700 BWPD at 7,535–8,040 ft; 5,400 BWPD at 12,976–13,568 ft) when tested.

Discussion

Formation test results for wells in the central Columbia Basin shown in table 1 indicate that both gas and condensate were recovered without water, or with either water or gassy water from several intervals. Based on limited data, water production is common, and the deeply buried sedimentary strata are apparently not continuously saturated with gas. Four tests in the Shell Yakima Mining Co. No. 1-33 well (SYM1, fig. 4) produced gas at very low rates, but without water, indicating a potential gas-saturated section between 10,604 and 12,430 ft. However, water was produced above and below this 1,800-ft-thick section. Additional testing is needed to confirm whether the 1,800-ft-thick zone is continuously gas saturated and not water wet.

Previous authors (for example, Tennyson and Parrish, 1987; Johnson and others, 1997) have suggested that coal beds within the Eocene Roslyn Formation are a source for natural gas and condensate in the Columbia Basin. Careful inspection of mud logs, sample descriptions, and caliper and density logs in the deep exploration wells indicates that coal beds are thin (less than 5 ft thick) and relatively rare, but fine-grained carbonaceous shale and mudstone were identified in sandstone, siltstone, and shale samples within the Roslyn Formation. In contrast to the log data, Tabor and others (1982) mapped banded bituminous coal seams ranging in thickness from 2 to 20 ft in the upper part of the Roslyn Formation in the Cle Elum area of central Washington (fig. 1). The coal beds may have been formed in shallow, short-lived swamps that were frequently covered by volcanic ash, lava flows, or arkosic fluvial sediments. This organic material may be a widespread but disseminated source for gas generation, but there is little available subsurface information on the overall volume of coal and carbonaceous shale within the Roslyn Formation. Total organic carbon (TOC) content in samples collected from the Roslyn Formation ranges from 0.92 to 17.09 percent (Tennyson and Parrish, 1987; Johnson and others, 1997). Other potential source rocks in the sub-basalt sequence include fluvial and lacustrine shales in the Eocene Swauk Formation (TOC, 0.03–1.10 percent) and Eocene Chumstick Formation (TOC, 0.13–5.97 percent) (Johnson and others, 1997). In general, little evidence exists to indicate that any of these possible source rocks generated enough gas to dewater potential reservoirs in the Columbia Basin.

One of the deep wells, the Shell Bissa No. 1-29 (SB1, fig. 4), penetrated a thick section of black shale and limestone near its total depth that was interpreted by Campbell (1989) to be lacustrine Swauk Formation. Shows of heavy gases (C3, C4, iC4), traces of oil in drilling mud, oil stain, fluorescence, and yellow solvent cuts were noted in an untested sandstone at 13,570 ft, just above the black shale. Fluorescence and yellow cut were noted in samples of limestone at 13,760 ft, within the black shale. The Swauk Formation may contain oil-prone, organic-rich source rocks and might be the source of condensates and heavy gases in the area.

Hydrocarbons present in deep wells in the Columbia Basin may have been derived from a dual-source system. Methane and light gases may have been expelled mainly from thin coal beds and disseminated carbonaceous material in the Roslyn Formation, whereas light oil, condensate, and heavy gases may have migrated vertically from shales in the Swauk Formation. Additional study is required to evaluate these possibilities.

Based on results of the deep exploratory wells drilled in the basin (table 1), it appears that structural or stratigraphic traps are important in identifying gas and condensate accumulations, although it is uncertain whether these traps represent sweet spots in a continuous basin-center gas accumulation or whether they are conventional traps. Care should be taken to avoid perforating and(or) fracturing reservoirs that produce water because the presence of water-producing zones makes the exploration process more difficult and risky. Petroleum exploration in the basin is complicated by the challenges involved in acquiring reliable geophysical images of potential structural or stratigraphic traps beneath the thick basalt flows.

Conclusions

The Columbia Basin has many of the attributes of a basin-center gas accumulation, including: overpressuring, high temperature gradients, thermally mature gas-prone source rocks, gas and condensate shows, and low-porosity, low-permeability sandstone reservoirs. Formation test results were evaluated for deep exploratory wells in the Eocene Wenatchee, Roslyn, and Swauk Formations beneath the Columbia Basalt Group. Some intervals were unproductive, and no measurable fluids or gas was recovered. Other intervals were gas- or condensate-bearing without water, were water-bearing, or contained gassy water. Hydraulic fracture stimulation tests were attempted to improve flow rates. One of these tests resulted in gas and condensate production at rates of 3,100 MCFD and 2 BCPD from a thin sandstone reservoir with good porosity. This reservoir interval, however, lies between zones that produced water at high rates. A second fracture stimulation test resulted in gas production at 500 MCFD, but the rate soon declined to 150 MCFD, and the zone was abandoned. Another stimulation test may have connected a gas-producing reservoir to a water-bearing zone, resulting in increased water production. The results of fracture stimulation have been mixed and indicate that there is a significant risk of connecting gas reservoirs with water-producing zones.

Test results indicate a possible gas-saturated interval without water in the Roslyn Formation between 10,604 ft and 12,430 ft in the Shell Yakima Minerals Co. No. 1-33 well. Gas was recovered at flow rates of 10 to 500 MCFD, but water also was recovered during formation testing above and below this zone. Additional testing is required to determine if the interval is actually continuously gas saturated.

Tertiary sedimentary strata below the Columbia Basalt Group evidently contain several water-bearing zones that are interbedded with gas-producing reservoirs. This relation implies that the available porosity in the sedimentary section is only partially saturated with hydrocarbons. Limited data indicate that a basin-center gas accumulation may exist, but further drilling and additional data are required for a more complete evaluation. The volume of mature source rocks may be relatively low and the gas expelled insufficient to dewater the available reservoirs, resulting in conventionally trapped gas accumulations. The sedimentary section may be crosscut by several fault and fracture systems that could serve as potential pathways for gas and fluids migrating upward into shallower zones. Quantitative assessment of basin-center gas must reflect the uncertainties associated with the limited geologic data.

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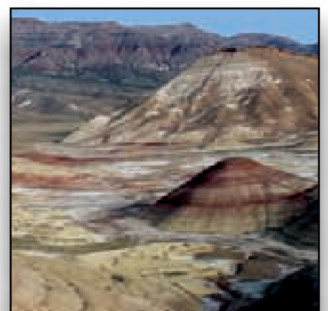

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