NATURAL RESOURCES

Petroleum Potential and Probability of Renewed Mineral-Rights Leasing in the Columbia Basin, Washington

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WASHINGTON
DIVISION OF GEOLOGY
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PETROLEUM POTENTIAL AND PROBABILITY OF RENEWED MINERAL-RIGHTS LEASING IN THE COLUMBIA BASIN, WASHINGTON

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EXPLANATORY NOTE

During 1994, the U.S. Army condemned various lands in the northwestern Columbia Basin in order to expand the Yakima Firing Range. The Army has offered Washington State $120 dollars per acre for approximately 11,400 acres of surface and mineral estate. (The Army now appraises the mineral rights as having zero value.) The State of Washington rejected the Army's offer and will challenge it in Federal District Court, Eastern Washington District, later this year (Cause No. CY-94-3113-AAM).

The following report was written to satisfy some rules of evidence for federal court. Compilation and interpretation of data and the written report were completed during a two week period in August 1995.

The writer was asked to provide information that would cover the breadth of possible testimony. Consequently, this report was not written as a scientific treatise and no particular effort made to achieve structurally coherent writing nor to explain standard petroleum industry jargon.

This report is included in the Division of Geology and Earth Resources library because it contains data and interpretations that may be of use to some readers.

ERRATA

Figures 2, 5, and 7 erroneously show the Bissa 1-29 well as the Bissa 1-39. The reference to Meridian should be as follows:

> Meridian Oil, Inc., 1987-1994, 23-35 BN: Washington Division of Geology and Earth Resources Oil and Gas Permit 424, 1 file.

August 24, 1995

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INTRODUCTION

This report assesses the probability that petroleum reserves underlie the northwestern Columbia Basin adjacent to the U.S. Army's Yakima Firing Range (Figure 1). Existing data and the history of petroleum exploration in similar "frontier" basins are used to provide information relating to the potential for commercial petroleum accumulations in the Columbia Basin that would, in turn, encourage petroleum companies and others to lease mineral rights.

Elements of Conventional Petroleum Accumulations

Conventional petroleum reserves are found in oil and/or gas fields that have the following elements:

(1) *A Basin* filled with sedimentary rocks. As a general rule, only sedimentary rocks contain significant sources of gas and oil. Most sedimentary basins produce at least some oil and/or gas; the larger and deeper the basin, the higher the probability of significant petroleum discoveries.

(2) *A Petroleum Source Rock* consisting of gas- or oil-prone organic material dispersed throughout the sedimentary rocks. Fossil marine or lacustrine plankton are the most common oil sources, whereas fossil plant fragments in claystones and siltstones are the most common source of non-associated gas.

(3) *A Thermal History* conducive to generation of petroleum. Normally this means minimum sustained geothermal heat of at least 100 degrees centigrade as measured at the depth of the source rock intervals.

(4) *A Reservoir*, typically consisting of pores between grains of sand in sandstone. World-class reservoirs generally average about 30 percent porosity. However, gas can be produced at great depth from sandstones having as little as 6 percent porosity.

(5) *A Trap* consisting of folds and/or faults together with impermeable strata that limit migration of low-density petroleum from the source to the surface. Petroleum migrates vertically because oil and gas float on the water that fills most porous sedimentary rocks.

Each of these five elements and other information relating to the potential for lease and royalty income on State School Trust Lands is discussed in the following sections.

Unconventional Gas Accumulations

There also significant potential for unconventional "basin-centered deep gas" accumulations in the Columbia Basin (Law, 1994). This type of accumulation, which has led to prolific production in Canada, is more likely to occur in areas with relatively poor reservoir characteristics, such as the deepest parts of the Columbia Basin. Although the elements of this type of gas accumulation are not reviewed in this report, many agree that Law is correct in his assertion that a basin-centered deep gas play is present in the Columbia Basin.

Figure 1. Index map showing locations of important northern Columbia Basin wildcat wells and major geographic features. RSH = Rattlesnake Hills.

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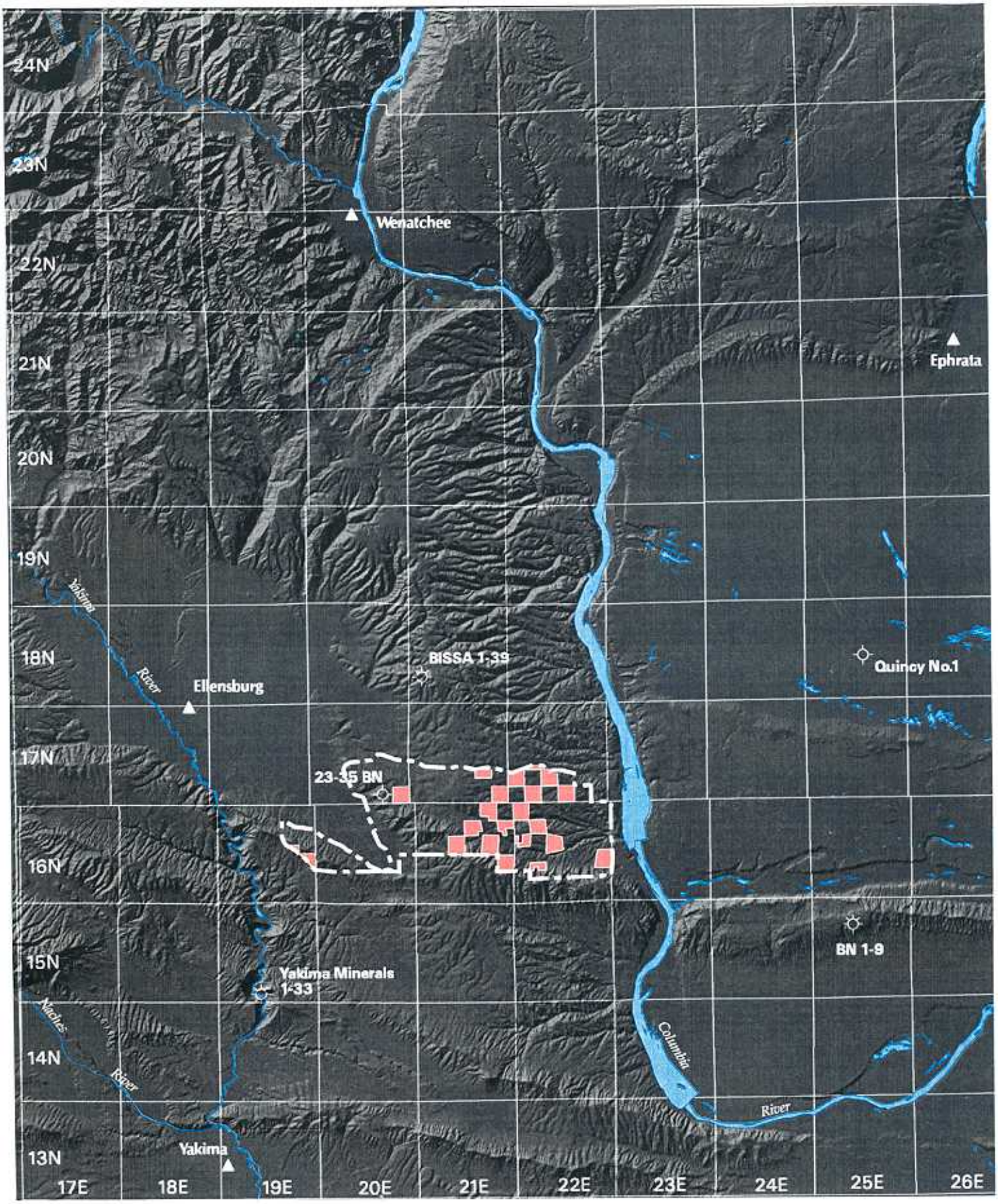
Figure 2. A topographic map showing landforms of the northern Columbia Basin and State Trust Lands (orange) located within the Yakima Firing Range Expansion Area (dashed white line). West-northwest trending ridges in the southern portion of the map are coincident with Miocene to Holocene anticlinal and/or faulted uplifts. Note that most of the State lands lie on top of a major north-trending topographic culmination in Townships 21 and 22 east (Hog Ranch - Naneum Ridge, Campbell, 1989).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Quincy No.1
23-35 BN
BN 1-9
Yakima Minerals 1-33
Naches River
Columbia River
Yakima

Historical Perspectives on Cycles of Exploration

Minerals-rights leasing activity is generally proportional to exploration effort. Exploration effort cycles as a function of supply and demand, as well as enthusiasm among oil companies for the prospects of any given basin. Lease values in the Columbia Basin mimic those in other frontier areas; these values fluctuate as a function of time and location and vary between zero and more than $120 per acre. Following an important discovery, or even enticing results from a drillstem test, lease bonuses skyrocket.

The following examples are typical of the relation between elimination of technological obstacles and renewed cycles of exploration.

Prior to 1930, common-depth-point reflection seismic technology had not been invented, and oil fields were discovered by mapping geology at the surface. Leases in areas with unfavorable surficial geology thus had zero value. Following invention of seismic technology, many giant fields were discovered worldwide, including dozens in formerly unproductive basins. For example, offshore Louisiana became a key exploration area as a result of seismic technology. In 1992, the average tract leased there for $472 per acre (Francois, 1993). In the most recent federal auction, mineral rights were leased for between $177 and $365 per acre, reflecting the depressed gas market (Oil and Gas Journal, 1994).

Prior to 1975, ninety-seven dryholes were drilled in the Idaho–Wyoming Thrust Belt and none had excellent shows. (Drilling down-dip from an oil seep that had been used to lubricate wagons on the Oregon trail yielded nothing.) Reservoir quality was assumed to be poor, and seismic data could not be used to "see" through complex folds and faults. Following improvements in the science of structural geology, seismic data were reinterpreted, and several giant fields were discovered. This area became a focus of onshore exploration in the United States. During the current depressed market, mineral rights in Idaho, a less prospective part of this frontier, have leased for $10 to $25 per acre with $1.00 annual lease rentals (Bill Van Bebber, independent landman, Denver, oral commun., 1995). The lease period is typically five years.

Prior to 1983, Papua–New Guinea had not produced any oil because seismic data could not "see" through complex folds and faults and the dense hard limestone at the surface. About 20 dryholes had been drilled looking for oil, but no discoveries were made until geologists understood Papua's structure and petroleum geochemistry sufficiently to map potential oil traps. Following improvements in structural geology and seismic data acquisition, several large or giant fields were discovered and new exploration provinces were "leased" for the first time.

Prior to 1994, more than 1,000 wells had been drilled through the Lodgepole Formation of the Dakotas and Montana without observing significant shows of petroleum. An accidental drillstem test in the Lodgepole Formation led to a major new exploration play. Approximate average lease values in that area are now $200/acre, and can be as much as $3,000 per acre (Larry Stavert, Team Leader, Rocky Mountain Exploration, Chevron USA, Houston, oral commun., 1995).

The current Gulf of Mexico sub-salt play, the San Juan Basin coalbed-methane play, and the Canadian basin-centered-gas play followed similar histories of new technology and/or good luck leading to aggressive exploration, leasing, and royalty income.

THE COLUMBIA BASIN

The Columbia Basin of central Washington and northern Oregon appears to be among the largest unexplored onshore sedimentary basin in the continental United States (Figures 1, 2, 3). It is larger than most of the petroleum productive basins in the Rocky Mountain states.

In the past, the Columbia Basin received little industry attention owing to a basalt cover ranging from a feather edge to about 15,000 feet in thickness. Deleterious acoustical effects of basalt can render conventional reflection seismic data, the chief tool of explorationists, uninterpretable. However, basalt cover is not an insurmountable obstacle. Similar plateau basalt terrains in Algeria and in the Western Siberian Basin produce petroleum from underlying reservoirs (Benelmouloud and Zhuralev, 1989).

The Columbia River Basalt Group is now known to overlie a thick section of sandstone and shale that contains some good reservoirs and has produced natural gas (Lingley and Walsh, 1986; Walsh and Lingley, 1991; Campbell and Reidel, 1994; Tennyson and Parrish, 1987). The section is composed of the Miocene Columbia River Basalt Group overlying Paleogene nonmarine siliciclastic rocks, which in turn, overlie Mesozoic rocks (Table 1). The last is mostly crystalline basement, but Mesozoic siliciclastic rocks and low-grade metamorphic lithologies crop out adjacent to the northern margin of the basin and could be locally present in the subsurface.

Columbia Basin wells flowed gas at rates that could yield as much as $3,740 per day as calculated using present-day depressed gas values ($0.68 at the Mist Field in August 1995; value from Dick Bowen, Northwest Oil Report, oral commun., 1995). Zones that yielded gas on tests of the Yakima Minerals 1-33 and BN 1-9 wells had lower porosity than adjacent zones. It is likely that this gas was trapped by the poor quality of these reservoirs (stratigraphic entrapment). Gas that flowed from the source into adjacent, better-quality reservoirs may have continued to migrate up dip. In that case, larger accumulations may be trapped in higher structural areas nearby.

Drilling data (Shell Oil Co., 1980-1988, 1980-1988, 1980-1991; Shell Western E & P, Inc., 1987-1992; Meridian Oil Co., 1989-1991) and various geophysical studies indicate that a thick sedimentary basin underlies parts of the Columbia River Basalt Group. Campbell (1989) estimates sedimentary strata (Paleogene nonmarine rocks) are about 31,824 feet thick in the Roslyn basin northwest of the Yakima Firing Range.

Figure 3 shows the possible extent and thickness of the Columbia Basin. Gravity and magnetic data suggest the basin is limited on the northwest by an extension of the Ross Lake fault. (This interpretation was suggested to the author by Shell Western E & P, Inc., oral commun., 1987.) The southeastern basin margin may be controlled near the 1-10 Darcell well by a northeast-trending fault that parallels the Hite fault. Seismic refraction data suggest the deeper part of the basin trends northwest and may be in the form of a graben or rift basin (Catchings and Mooney, 1988).

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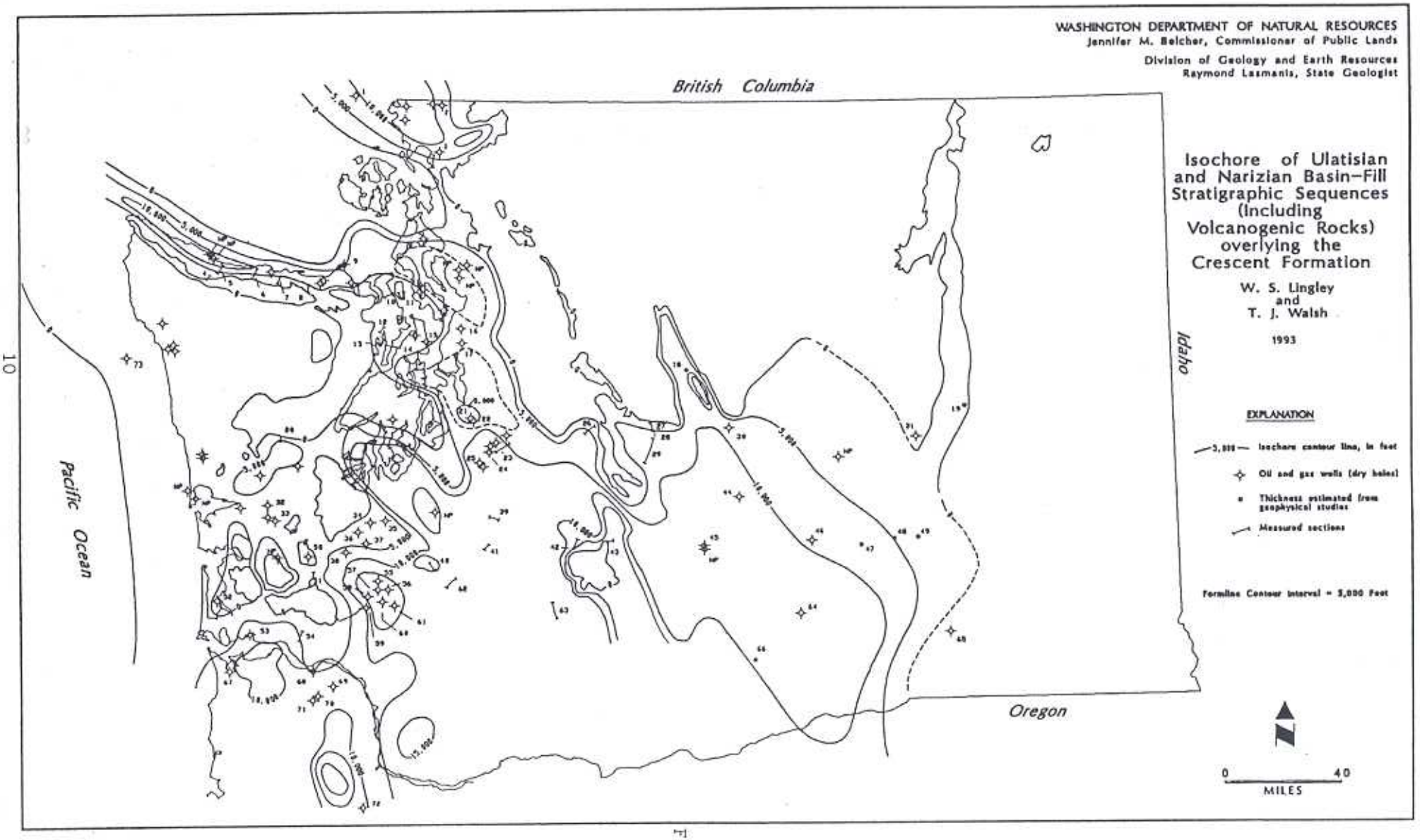
Figure 3. Isopach maps showing the possible thicknesses and distributions of Paleogene nonmarine rocks in the Columbia Basin and basins of western Washington (unpublished mapping by W. S. Lingley, Jr. and T.J. Walsh, 1993). Figure 3a shows mostly Eocene strata, and Figure 3b shows upper-most Eocene to Oligocene strata. The Columbia Basin is the area of thicker sediment preservation in the south-central part of the state.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Raymond Lasmanis, State Geologist
British Columbia
Isochore of Ulatisian and Narizian Basin-Fill Stratigraphic Sequences (Including Volcanogenic Rocks) overlying the Crescent Formation
W. S. Lingley and T. J. Walsh
1993
Idaho
EXPLANATION
5,000 — Isochore contour line, in feet
Oil and gas wells (dry holes)
Thickness estimated from geophysical studies
Measured sections
Formline Contour Interval = 5,000 Feet
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Oregon
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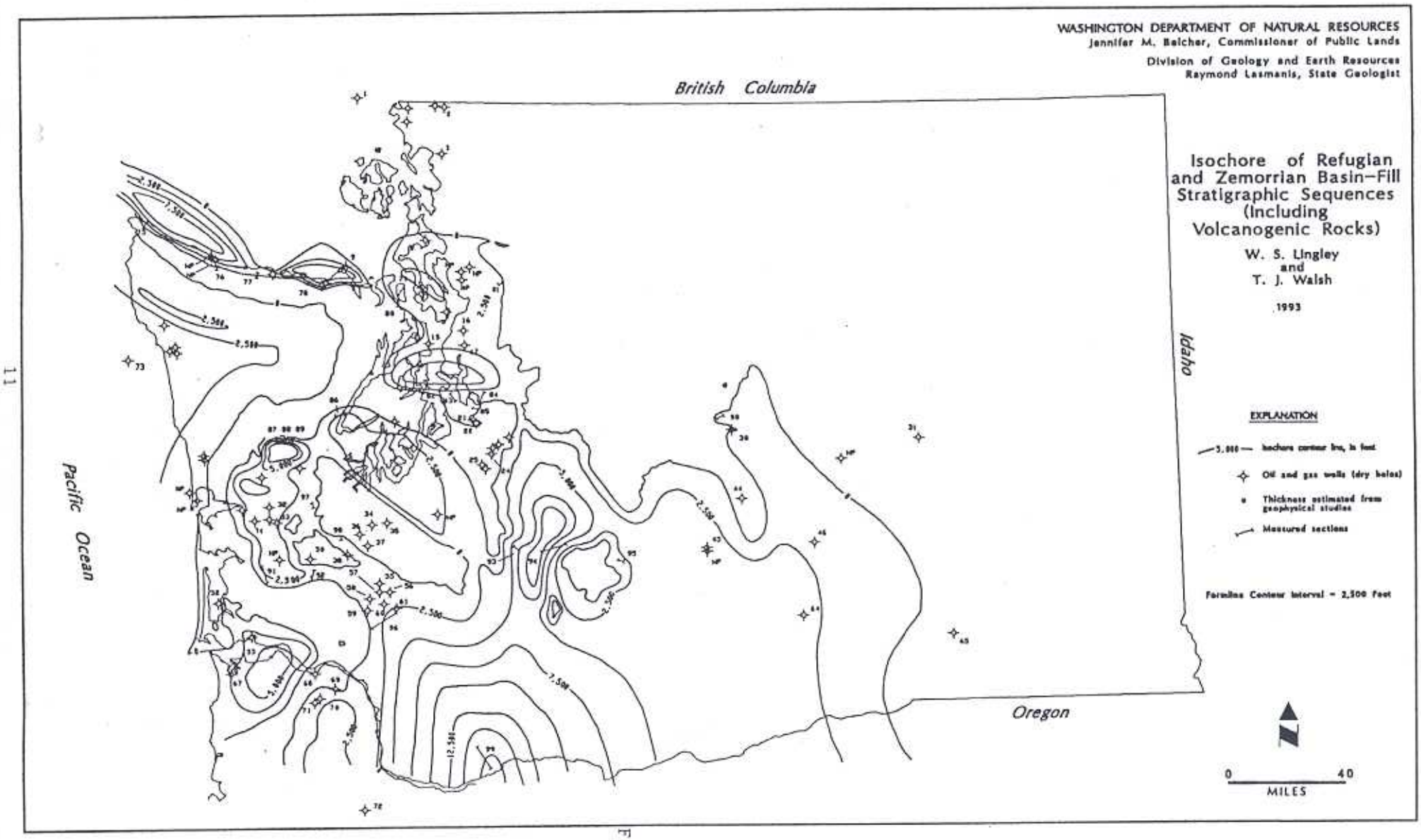
Figure 3a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EXPLANATION
Isochore contour line, in feet
Oil and gas wells (dry holes)
Thickness estimated from geophysical studies
Measured sections
Formline Contour Interval = 2,500 feet
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40
MILES

Figure 3b

A generalized stratigraphic sequence for the Columbia Basin is given in Table 1. Unit tops listed in industry reports are presented, rather than other published choices because industry had access to biostratigraphic expertise, radiometric dating, engineering data, reflection seismic profiles, and other expensive information that would add reliability to their choices. For lithostratigraphic tops, Campbell and Reidel (1994) present results of a thoughtful analysis.

IMPETUS FOR CONTINUED EXPLORATION AND LEASING

Giant Petroleum Fields

The impetus for continued exploration in the Columbia Basin will come from recognizing the potential for large or giant natural gas discoveries. About 85 percent of the world's oil and gas is produced from giant fields (Halbouty, 1980). Of approximately 25,000 fields in the United States, Halbouty (1970) reasonably projected that about 10 percent would yield approximately 60 percent of the ultimate production.

While many small oil and gas fields remain to be discovered in the United States, closely spaced drilling in most onshore basins diminishes the probability of large discoveries because the remaining unexplored area is insufficient for typical large petroleum fields. For this reason, large independent and major oil companies focus exploration in frontier basins.

For example, the Powder River Basin, a productive basin in northeastern Wyoming that is slightly smaller than the Columbia Basin, has had more than 27,000 wells drilled for oil and gas. In contrast, the Columbia Basin, where only eight deep wells have been drilled, is the least explored, large onshore basin in the United States (Lingley and Walsh, 1986; Johnson and others, 1993). During the past four decades, most giant fields have been discovered by mapping new frontier basins using reflection seismic data (Halbouty, 1980).

Current Low Level of Interest

In the past few years, the price of natural gas in the United States has fallen from more than $2.50 per thousand cubic feet (MCF) in 1984 to less than $1.00 per MCF. Diminished gas values are due to market forces that include U.S. and Canadian gas discoveries. Many of these discovery wells were drilled in response to improved economics caused by the alternative fuels tax credit (no longer available). Mineral rights for lands with potential to produce only natural gas will not be leased until the price of gas recovers. Although some analysts have suggested that the price of natural gas will remain at a low, price recovery could occur at any time—more than 60 percent of the United States' petroleum is imported from countries that could choose to restrict the supply.

Other obstacles hinder exploration and consequent leasing in the Columbia Basin: (1) the expense of drilling through hard basalt, (2) the difficulty of obtaining seismic data of acceptable quality, and (3) the likelihood that gas rather than oil will be discovered in the basin.

Drilling costs would not be considered an impediment if the price of gas were significantly higher or if a commercial gas discovery were drilled in the basin. The latter would reduce

TABLE 1. Formation and unit tops for northwestern Columbia Basin wells that penetrated Paleogene nonmarine rocks underlying the Columbia River Basalt Group.

WELL — GEOLOGIC UNIT	TOP (feet)	THICKNESS (feet)
Quincy No. 1 (Shell Western E & P, Inc., 1987-1992)		
Wanapum Basalt	144	796
Grande Ronde Basalt	940	6,607
Paleogene nonmarine	7,547	5,234
Eocene (Swauk Fm.)[1]	7,547	5,234
coal-bearing interval	10,017	533
Basement (schist)	12,781	-
Total depth	13,200	
23-35 BN [Boylston Mountain well] (Meridian Oil, Inc., 1989-1991)		
Columbia River Basalt Group	0	6,658
Paleogene nonmarine	6,658	>5,926
Oligocene	6,658	2,312
Eocene (Roslyn Fm.)	8,970	3,614
coal-bearing interval	9,110	436
Teanaway Basalt	12,347	?
Total depth	12,584	
BN 1-9 [Saddle Mountains well] (Shell Western E & P, Inc., 1980-1991)		
Saddle Mountains Basalt	0	210
Wanapum Basalt	210	877
Grande Ronde Basalt	1,087	11,713
Paleogene nonmarine	12,800	4,718
Oligocene	12,800	2,000
Eocene (Chumstick Fm.)	12,800	4,718
coal-bearing interval	11,994	276
2nd coal interval	15,114	694
Total depth	17,518	
Bissa 1-29 [Whiskey Dick well] (Shell Oil Co., 1980-1988)		
Columbia River Basalt Group	0	4,512
Paleogene nonmarine	4,512	10,388
Eocene	4,512	?
coal-bearing interval	4,626	2,268[2]
Basement ? (granitic mega-conglomerate?)	14,900	?
Total depth	14,965	
Yakima Minerals 1-33 [Rosa Dam well] (Campbell and Reidel, 1994 [approximate depths])		
Columbia River Basalt Group	0	4,926
Paleogene nonmarine	4,926	11,273
Oligocene	4,926	4,774
Eocene	9,700	6,499
Total depth	16,199	

1. Campbell and Reidel (1994) report a thick Oligocene section in this well.
2. Coal thicknesses in Bissa 1-29 suspect owing to severe cavings that contaminated the ditch cuttings.

the uncertainty of prospects in the basin and thereby improve the economics of wildcat drilling. The normal pattern of basin development is cyclical leasing that peaks each time a new idea or technological breakthrough occurs.

Acquisition of interpretable seismic data in basalt has been particularly difficult because of low signal-to-noise ratios and because of poor coupling between the seismic signal receivers and basalt outcrops. Complex faulting in the vicinity of the Yakima Firing Range (Tolan and Reidel, 1989; Price and Watkinson, 1989; Reidel, 1984; Reidel and Campbell, 1989; Campbell, 1989) also diminishes the quality of seismic records. (However, this complexity may be an advantage because complex faulting generally results in numerous potential petroleum traps.)

It may now be possible to acquire seismic data of reasonable quality in the Columbia Basin. A technological innovation (Jarchow and others, 1991, 1994) now allows geophysicists to locate the base of the basalt accurately and at low cost. Such seismic data could be used to produce a regional map of the base of the Columbia River Basalt Group. This map could be integrated electronically with data from other geophysical tools in order to produce prospect-scale mapping. Withers and others (1994) used a similar integration technique to produce accurate prospect-scale maps below the basalt in the southern part of the Columbia Basin.

In the past, the high probability of gas (as opposed to oil) discoveries in the basin also discouraged exploration. Traditionally gas has a soft market because of high transportation costs. Gas pipeline construction can cost $40 per linear foot. However, environmental emphasis on gas as a non-polluting fuel, together with a shortage of domestic oil will strengthen gas markets in the near future. Even if other fuel sources are developed, gas will continue to be an important petrochemical feedstock. For example, production of some fertilizers requires large amounts of natural gas.

SOURCE ROCKS

Columbia Basin Shows and Production

The clearest indications that petroleum source rocks are present in any given sedimentary basin is oil or gas seeps at the ground surface and petroleum tested or produced from wells. The Columbia Basin has both (Table 2).

Gas-prone source rocks are evidently present in abundance in the basin. Gas shows are so common that almost all of the sandstone reservoirs in the Paleogene nonmarine section have at least some gas saturation.

A small gas field, located in a subsidiary fold on the north flank of the Rattlesnake Hills anticline, lies south of the Yakima Firing Range (Figure 1). It produced 1.3 billion cubic feet of natural gas before it was abandoned in 1941 (Hammer, 1934; McFarland, 1983). This field is unique in that gas was produced from the Columbia River Basalt Group. A similar but non-commercial gas accumulation appears to be trapped in part by the Cold Creek fault (Johnson and others, 1993). Johnson and others' delta ^{13}C isotopic ratios, together with the projected thickness of basalt (estimated from Grande Ronde data given in Reidel and others, 1989) suggest that both gas accumulations were generated from a deep source. The source may have been a basin-centered-gas system, coals between basalt flows, or the Paleogene nonmarine section. If the latter is correct, part of the gas may have migrated upward along faults through at least 13,000 feet of basalt.

The Yakima Minerals 1-33 well tested 500 thousand cubic feet of gas per day (MCFGPD) and the BN 1-9 well tested 5,500 MCFGPD (Table 2). If these rates could have been sustained, both may have been completed as discovery wells. Southeast and southwest dips recorded on dipmeter log interpretations from the BN 1-9 and Yakima Minerals 1-33 wells, respectively, suggest that neither well was drilled on a structural apex. (See notes on Table 4.) Therefore, it is possible that gas accumulations are trapped updip from these wells.

Completion of discovery wells drilled in close proximity to dryholes is a common occurrence in the petroleum industry. The Anoa field in Indonesia, for example, produced oil within a few hundred feet of a down-dip dryhole. Gulf Oil Companies discovery well 1.5 miles up-dip from an abandoned AGIP Oil Company dryhole and to drill the 50-million barrel discovery. Another example is the Mist Gas Field of northwestern Oregon, which has produced more than 50 billion cubic feet of gas (BCF) from a 100-acre fault trap within a larger anticline (Olmstead, 1985). A dryhole had been drilled on the anticline prior to the discovery well. The discovery well was initially abandoned, but it was re-entered and whipstocked to reach the updip gas pool located only a few linear feet from the vertical portion of the hole.

Geochemistry of Source Intervals

Table 3 and Figure 4 summarize some geochemical characteristics of these rocks as determined from analyses of samples from four wells (Core Laboratories, Inc., 1987a,b; Lingley and Walsh, 1986; Lingley and von der Dick, 1991; Walsh and Lingley, 1991). (Also see Brown and Ruth Laboratories, Inc., 1984; Sidle and Richers, 1985; U.S. Dept. of Energy, 1985.)

New geochemical data (Core Laboratories, Inc., 1987a, b) summarized in Table 3 confirm that both the Yakima Minerals 1-33 and the Bissa 1-29 penetrated thick sections of good-quality gas-prone source rocks. In the Bissa well, a continuous 1,980-foot-thick section averages 4.2 percent total organic carbon (TOC). Pyrolysis data for this section indicate that these rocks are thermally mature and have moderate to good gas-generative potential (Table 3). The Yakima Minerals 1-33 well has a continuous 1,230-foot-thick section favorable for gas generation; TOC averages 2.63 percent with some favorable S_1 and S_2 values. Although the source interval in the Yakima Minerals well is not as rich or thick as in the Bissa well, it is at slightly greater depth, and consequently it has generated more gas (mean S_1 = 0.69). A pseudo van Krevelen diagram (Figure 4) shows that these proven source rocks are gas prone and that traces of exinitic and/or liptinitic macerals are also present (hydrogen indices [HI] >200). These Type II kerogens probably generated the paraffinic condensate (37 to 52 degrees API gravity) tested in the BN 1-9 well. These rocks have mostly woody and amorphous material that would reach peak generative potential at vitrinite reflectance values of about 0.8 (Peters, 1986).

No information is available to link shows with corresponding source rocks. Hydrous pyrolysis of Type II coals and adjacent shales penetrated in a well drilled in western Washington indicates that both shales and coals have potential to generate light hydrocarbons.

Graben-fill sequences along the margins of the Columbia Basin (Table 3; Gaylord, 1986) also have limited gas-generative potential. However, these rocks are mostly super-mature and impoverished.

TABLE 2. Significant shows of petroleum from northern Columbia Basin wells.

Quincy No. 1 (Shell Western E & P, Inc., 1987-1992)

Perforations from 8,765 to 8,915 ft and 8,779 to 8,886 ft produced gas TSTM and 500 BW.

23-35 BN [Boylston Mountain well] (Meridian Oil, Inc., 1989-1991)

Drillstem test from 11,919 to 12,584 ft. No data reported. Abundant cutting gas shows throughout the Paleogene nonmarine section.

BN 1-9 [Saddle Mountains well] (Shell Western E & P, Inc., 1980-1991)

12 gas zones reported. 4 production tests. Acidized and fraced perforations from 12,694 to 12,699 ft produced 2.4 MMCFGPD and 134 BWPD with 985 psi FTP on 20/64-inch choke. A test through casing from 13,372 to 13,388 ft. produced 3.1 MMCFGPD and 6 BCPD with 3,965 FTP on 10/64-inch choke.

Bissa 1-29 [Whiskey Dick well] (Shell Oil Co., 1980-1988)

Acidized perforations from 10,314 to 10,898 ft, 9,436 to 9,830 ft, and 8,486 to 8,800 ft flowed gas TSTM.

Yakima Minerals 1-33 [Rosa Dam well] (Shell Oil Co., 1980-1988)

Acidized perforations from 15,466 to 15,540 ft recovered small amounts of gas. Perforations from 12,976 to 13,568 flowed 570 MCFGPD and 5,400 BWPD with 3,250 psi FTP on 24/64-inch choke. Fractured and acidized perforations from 12,450 to 12,460 ft and 12,350 to 12,360 ft flowed 500 MCFGPD. Acidized perforations from 11,676 to 11,686 ft, 11,564 to 11,574 ft, and 11,598 to 11,652 ft flowed gas at 85 MCFGPD. Perforations from 10,604 to 10,930 flowed 10 MCFGPD. Perforations from 7,535 to 8,040 ft flowed 1,700 BWPD and 27 MCFGPD.

Norco No. 1 [Wenatchee well] (McFarland, 1983)

Gas shows reported.

Rattlesnake Hills Gas Field (Hammer, 1934)

Produced 1.3 BCF gas from 16 wells producing between 700 and 1,200 ft at 7 psi FTP. Gas was piped to Yakima for sales.

Water wells (Johnson and others, 1993)

19 water wells located between Yakima and Pasco have tested thermogenic gas and several have had degassing equipment installed.

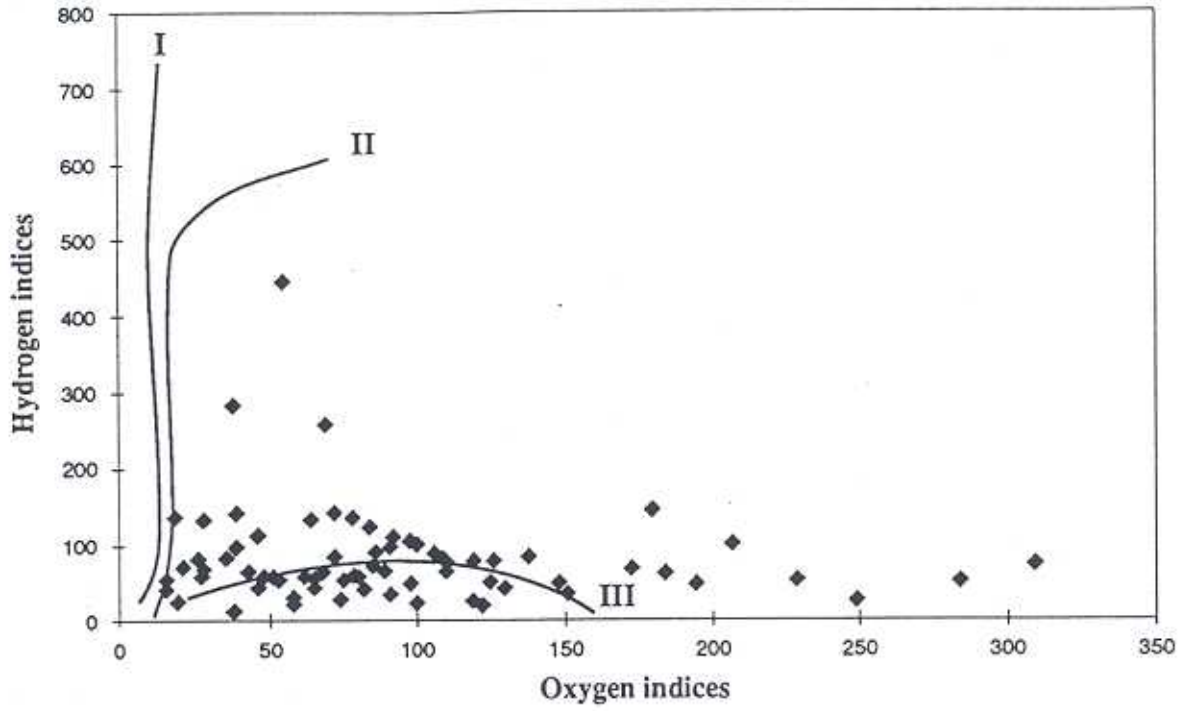

Figure 4. A pseudo van Krevelen diagram for Paleogene nonmarine strata penetrated in the Yakima Minerals 1-33 and Bissa 1-29 wells (Core Laboratories, Inc., 1987a, b). Both wells have an abundance of gas-prone source rocks (Type III kerogen) with traces of Type II kerogen (light-liquids- and gas-prone).

Although gas and gas-condensate shows have been recorded throughout the Paleogene nonmarine section, no oil shows have been observed. Much of the sedimentary section in the basin lies within the oil-generative thermal window (Table 3, Figure 5). Therefore, it can be inferred that if areally extensive oil-prone source rocks were present in the basin, oil shows should have been observed. However, the possibility of an oil discovery cannot be ruled out at this time because so few holes have penetrated the Paleogene nonmarine section.

In summary, the area of the Firing Range Expansion overlies a thick section of proven gas-prone source rocks that are of moderate to good quality. Data from the Bissa and Yakima Minerals wells indicate that the area of State Trust Lands north of the Firing Range may have thicker source intervals than areas located farther south. Gas tested in the BN 1-9 confirms that this well is also located over a good gas source.

THERMAL HISTORY

Blackwell and others (1985) show that Columbia Basin geothermal gradients range from 28 to 58 degrees centigrade per kilometer (Figure 5). Lingley and Walsh (1986) used wireline log and drillstem test data from the northwestern Columbia basin wells to show that typical geothermal gradients are +/-40°C/kilometer. Such gradients are optimally conducive to generation and preservation of petroleum. They suggest that the onset of gas generation should occur at about 7,000 feet.

Vitrinite reflectance (R_0) values from all of the Columbia Basin wells range from 0.5 to 1.3 demonstrating that the entire sub-basalt section drilled to date is thermally mature for gas generation. Figure 5 shows depths to $R_0 = 0.5$, the value corresponding to the onset of peak gas generation from woody amorphous kerogen.

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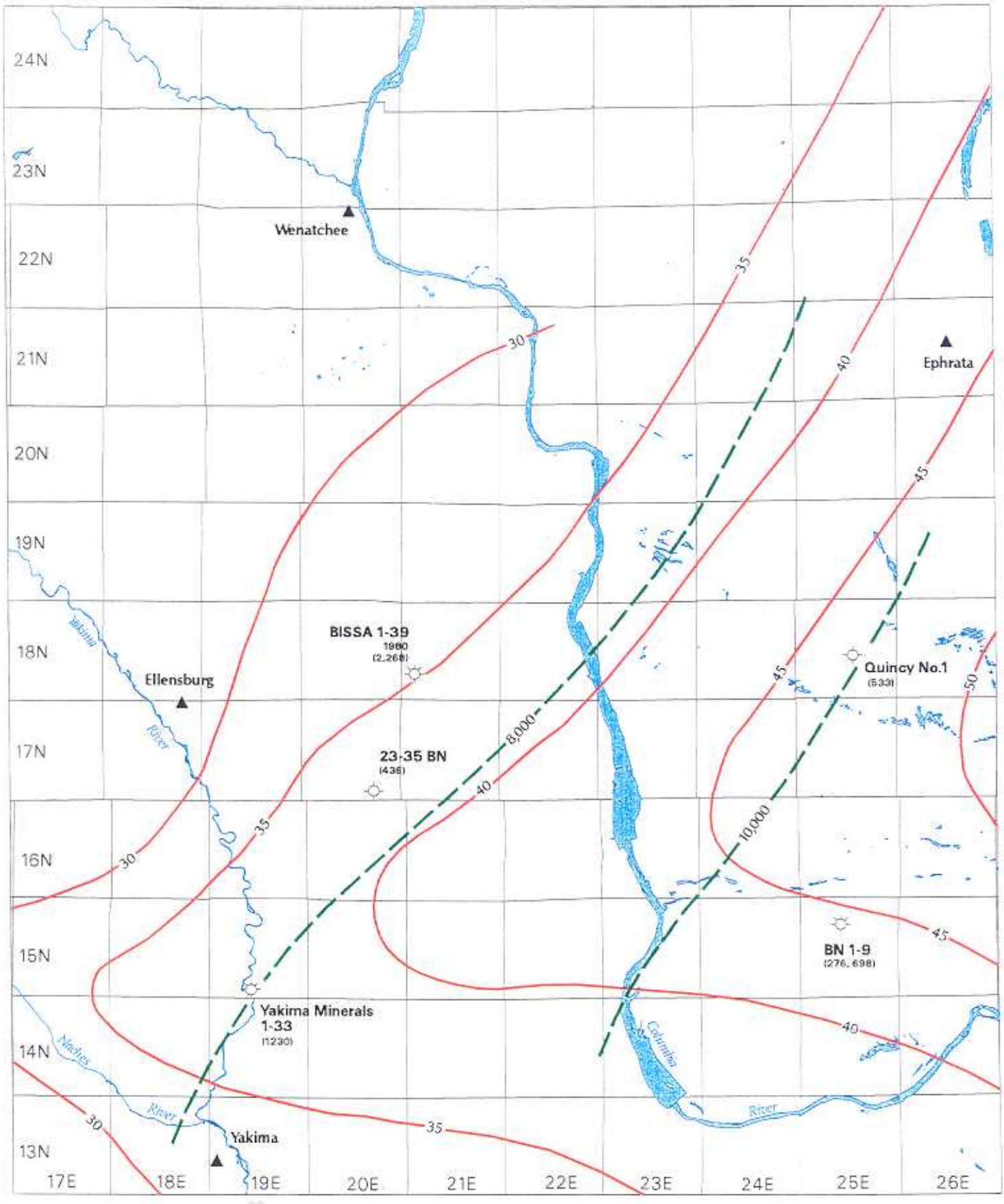
Figure 5. A summary of some northwestern Columbia Basin maturation and organic facies data. Green contours shows approximate depths to vitrinite reflectance = 0.5 (after Walsh and Lingley, 1991). Red contours show approximate geothermal gradients in degrees centigrade per kilometer (from Blackwell and others, 1985). The numbers in parentheses give the thicknesses of sections with some bedded coal and are indicative of reducing environments favorable to carbon preservation. Numbers beside the Yakima Minerals 1-33 and Bissa 1-29 indicate sections having continuous TOC values greater than 0.80 (Core Laboratories, Inc., 1987a,b).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24E
25E
26E
Wenatchee
Ephrata
Ellensburg
Yakima
BISSA 1-39
1980
(2,268)
23-35 BN
(438)
Quincy No.1
(533)
BN 1-9
(276, 698)
Yakima Minerals
1-33
(1230)
Yakima River
Naches River
Columbia River
30
35
40
45
50
8,000
10,000

Table 3. Source-rock analyses of Columbia Basin wells and outcrops (Core Laboratories, Inc., 1987a,b; Lingley and von der Dick, 1991).

	from Depth	to Depth	TOC	HI	OI	S1	S2	S3	Tmax	Ro
Herren Fm[1]				4.80						0.70
Bissa 1-29										
	4800	4830	0.00	97					432	
	4900	4910	0.52	108					426	
	5250	5280	1.15	143					434	
	5410	5430	0.60	80					435	
	5580	5610	0.63	130					430	
	5700	5730	0.57	61					441	
	5790	5820	0.58	45					454	
	5880	5910	0.59	47					441	
	5970	6000	1.00	99					431	
	6060	6090	1.20	159					433	
	6150	6180	5.15	226					425	
	6240	6270	9.67	181					424	
	6330	6360	3.94	193					426	0.66
	6420	6450	5.87	175					428	
	6510	6540	4.14	153					430	
	6600	6630	4.96	159					428	
	6690	6720	3.44	87					434	
	6780	6810	16.08	193					425	
	6870	6900	17.17	215					421	
	6960	6990	0.96	88					431	
	7050	7080	1.44	115					430	
	7140	7170	2.57	143					431	
	7230	7260	1.96	157					432	0.61
	7320	7350	0.98	123					432	
	7590	7620	1.61	145					432	
	7680	7710	0.85	91	86	0.10	0.77	0.73	435	0.65
	7770	7800	0.98	144	72	0.12	1.41	0.71	434	
	7860	7890	1.09	144	39	0.10	1.57	0.43	435	
	7920	7950	3.26	284	38	0.29	9.25	1.25	433	
	7950	7980	0.52	90	106	0.05	0.47	0.55	435	
	8040	8070	0.53	106	98	0.07	0.56	0.52	434	

Depth	Depth	TOC	HI	OI	S1	S2	S3	Tmax	Ro
8130	8160	0.90	124	84	0.11	1.12	0.76	433	0.68
8310	8340	0.50	102	100	0.07	0.51	0.50	435	
8410	8430	0.63	111	92	0.11	0.70	0.58	433	
8460	8490	2.71	259	69	0.28	7.01	1.88	434	
8580	8610	1.56	134	64	0.14	2.09	1.00	434	0.63
8970	9000	3.30	25	19	0.19	0.84	0.63	438	
9540	9570	0.79	66	68	0.10	0.52	0.54	437	
11370	11400	0.56	114	46	0.09	0.64	0.26	448	
11940	11970	0.58	447	55	0.48	2.59	0.32	456	
13080	13110	0.83	99	39	0.28	0.82	0.32	463	
13140	13170	3.71	85	35	0.71	3.14	1.31	455	
13530	13560	0.55	85	36	0.20	0.47	0.20	468	
13680	13710	1.72	84	26	0.55	1.45	0.45	455	
13710	13740	1.10	64	184	0.29	0.70	2.02	458	
13800	13830	1.15	41	82	0.16	0.47	0.94		
13890	13920	1.40	50	98	0.21	0.70	1.37	459	
13980	14010	1.55	59	62	0.31	0.91	0.96	467	1.12
14070	14100	1.44	30	58	0.20	0.43	0.84		
14160	14190	1.15	56	53	0.25	0.64	0.61	462	
14250	14280	0.93	54	15	0.22	0.50	0.14	465	
14340	14370	0.81	44	46	0.21	0.36	0.37	472	
14430	14460	1.12	83	109	0.29	0.93	1.22	448	1.16
14520	14550	0.79	41	15	0.14	0.32	0.12		
14610	14640	1.00	59	48	0.22	0.59	0.48	470	
14700	14730	1.24	46	65	0.24	0.57	0.80	486	
14790	14820	1.18	54	75	0.26	0.64	0.88	471	
14890	14910	1.16	60	79	0.33	0.70	0.92	469	
14110	14111	1.20	59		0.30	0.70		453	
14360	14361	0.50	53		0.10	0.30		466	
14860	14861	1.40	45		0.30	0.60		459	
13610	13611	0.80	64		0.10	0.50		459	
14360	14361	0.90	74		0.30	0.70		453	
13760	13761	1.30	64		0.20	0.80		464	

	Depth	Depth	TOC	HI	OI	S1	S2	S3	Tmax	Ro
	13610	13611	0.80	60		0.10	0.50		457	
	13760	13761	1.30	65		0.20	0.80		458	
	14860	14861	1.30	40		0.30	0.50		464	
	14110	14111	1.10	63		0.20	0.70		455	
Yakima Minerals										
	4980	5010	0.58	55	229	0.06	0.32	1.33	432	
	6600	6630	0.61	164	551	1.05	1.00	3.36	432	
	8670	8700	0.62	53	284	0.22	0.33	1.76	432	
	9840	9870	1.02	67	110	0.15	0.68	1.12	467	
	10020	10050	1.06	99	91	0.32	1.05	0.96	460	
	10110	10140	1.37	137	78	0.48	1.88	1.07	455	1.02
	10200	10230	3.26	148	180	2.20	4.84	5.86	451	
	10290	10320	7.47	134	28	1.88	10.00	2.11	459	
	10380	10410	7.50	138	18	1.86	10.33	1.32	461	
	10470	10500	2.02	85	72	0.36	1.72	1.46	461	
	10560	10590	1.65	79	126	0.34	1.31	2.08	463	1.19
	10650	10680	0.89	74	85	0.20	0.66	0.76	475	
	10750	10770	0.81	78	110	0.18	0.63	0.89	472	
	10920	10950	1.22	57	65	0.20	0.70	0.79	490	
	11010	11040	3.51	60	27	0.40	2.12	0.94	474	1.33
	11040	11070	2.47	68	28	0.38	1.67	0.70	477	
	11100	11130	0.63	51	148	0.15	0.32	0.93	485	
	11190	11220	0.69	59	80	0.16	0.41	0.55	485	
	11310	11340	2.05	72	21	0.38	1.48	0.44	474	
	11370	11400	0.82	66	43	0.17	0.54	0.35	480	
	11460	11490	0.81	80	119	0.23	0.65	0.96	459	1.22
	11650	11670	0.56	86	138	0.21	0.48	0.77	476	
	11730	11760	0.53	136	775	0.27	0.72	4.11	476	
	11820	11850	1.22	44	130	0.11	0.54	1.58	501	
	11910	11940	1.32	67	89	0.27	0.89	1.18	492	1.43
	12000	12030	1.28	59	51	0.24	0.76	0.65	483	
	12100	12120	0.74	76	309	0.38	0.56	2.29	482	
	12270	12300	0.73	52	125	0.15	0.38	0.91	482	

	Depth	Depth	TOC	HI	OI	S1	S2	S3	Tmax	Ro
	13260	13290	0.71	104	207	0.50	0.74	1.47	482	
	13980	14010	1.42	23	58	0.41	0.32	0.83	482	
	14040	14070	0.61	23	100	0.23	0.14	0.61	482	
	14340	14370	0.53	28	74	0.25	0.15	0.39	482	
	14430	14460	0.74	35	91	0.33	0.26	0.67	482	
	14520	14550	0.89	78	663	0.21	0.69	5.90	482	
	14610	14640	0.99	26	249	0.21	0.26	2.47	482	
	14700	14730	0.90	70	173	0.38	0.63	1.56	482	
	14790	14820	1.23	63	185	0.26	0.77	2.28	482	
	15390	15420	0.69	20	122	0.20	0.14	0.84	482	
	15420	15450	0.77	36	151	0.28	0.28	1.16	482	
	15540	15570	0.83	25	119	0.21	0.21	0.99	482	
	15690	15720	1.38	49	195	0.34	0.67	2.69	482	
	16140	16170	0.85	13	38	0.36	0.11	0.32	482	
MEANS				92.55	116	0	1.21	1.17		
Virginia Ridge Fm[2]									0	
			0.05			0.00	0.00		0	
			0.11			0.00	0.00		0	
			0.18			0.00	0.00		0	
			0.05			0.00	0.00		0	
			0.13			0.30	0.00		0	
			0.10			0.00	0.00		0	
			0.05			0.00	0.00		0	
			0.12			0.01	0.02		277	
			0.08			0.28	0.08		294	
			0.18			0.02	0.05		277	
			0.06			0.00	0.01		257	
			0.13			0.28	0.01		252	
			0.19			0.01	0.03		270	
			0.00			0.02	0.04		486	
			0.00			0.02	0.03		481	
			0.16			0.01	0.02		296	
			0.17			0.01	0.00		0	

	Depth	Depth	TOC	HI	OI	S1	S2	S3	Tmax	Ro
			0.19			0.01	0.01		323	
			0.22			0.02	0.10		479	
			0.19			0.03	0.08		296	
			0.13			0.04	0.02		332	
Harts Pass Fm[2]										
			0.12			0.00	0.00		0	
			0.17			0.00	0.00		0	
			0.12			0.00	0.00		0	
			0.02			0.00	0.00		0	
			0.13			0.00	0.00		0	
			0.23			0.00	0.00		0	
			0.13			0.00	0.00		0	
			0.14			0.01	0.02		277	
			0.11			0.00	0.01		277	

1. A sample from the Herren Fm. of northern Oregon, which is equivalent to the Paleogene nonmarine section (Fritts and Fisk, 1985) is included for comparison.
2. Characteristics of some Mesozoic siliciclastic rocks are included because these rocks could subcrop in parts of the basin.

RESERVOIRS

Reservoir data for wells drilled near the Yakima Firing Range are summarized on Figures 6 and 7 and Table 4. This table lists only moderate to good quality reservoirs, those reservoirs with 10 percent or greater porosity and that are thicker than 10 feet. Comparison with porosity data from several large Rocky Mountain oil fields (Table 5, Figure 8) confirms that such reservoirs are adequate to contain large to giant petroleum reserves. Note, however, that natural gas production can be achieved from lower quality reservoirs, especially if those reservoirs are at great depth. (Deeper reservoirs store more gas per unit volume and generally produce the gas at faster rates.) The BN 1-9, for example, produced a remarkable 3,100 MCF of gas from a zone with only 7 percent average porosity (Shell Western E & P, Inc., 1984-1991).

Lingley and Walsh (1986) determined that mean sandstone porosity in the Columbia Basin, expressed as a percentage of the bulk volume of the rock, is 18 percent at 6,000 feet drilled-depth. Mean sandstone porosity is reduced to 8 percent at 14,000 feet, regardless of the age or composition of the sandstone present at this depth. New data from the 23-35 BN and Quincy No. 1 wells support their findings (Fig. 6).

Both the average porosity and average thickness of reservoir sandstones in the Columbia Basin are good, and comparable to typical Rocky Mountain sandstone reservoirs. The average porosity of thick Paleogene nonmarine sandstones penetrated above 11,000 feet in the Columbia Basin is about 15 percent (Fig. 6). Table 4 shows that the average thickness of sandstone reservoirs logged in the northwestern Columbia Basin wells with greater than 10 percent porosity is 25 feet. Sandstones having continuous porosity in excess of 30 feet are common.

The aggregate thickness of moderate- to good-quality reservoirs is shown on Figure 7. Net porous sandstone in the Yakima Firing Range Expansion Area ranges from 250 to 400 feet. Farther east and southeast, the sandstones are at greater depth owing to greater thickness of overlying basalt. If the Quincy No. 1 results are representative, then there is less sandstone northeast of the Expansion Area.

Clay volume (Vclay) and the percentage of volcanogenic detritus affect reservoir quality in the Columbia Basin. Studies of outcrop data and ditch samples (Campbell, 1989) suggest areas southwest of the Firing Range are dominated by clay-rich volcaniclastic rocks of the Naches subbasin. Sandstones deposited farther north and east are dominated by more favorable quartz- and feldspathic-arenites.

Therefore, State School Trust Lands appear to be in an optimal position between reservoirs of higher average porosity, greater total reservoir thickness, and less detrimental clay or volcanogenic rock.

TABLE 4. Some reservoir properties of sandstones that are greater than 10 feet thick and have greater than 10 percent porosity.

Interval (ft)	Net Porosity (ft)	Vclay (%)	Mean Porosity (%)
Quincy No. 1[1]			
8,283 - 8,305	22	6	15
9,265 - 9,280	15	8	17
9,390 - 9,421	31	32	18
10,171 - 10,188	12	13	19
Net & means	**80/20**	**15**	**17**
23-35 BN (Boylston Mountain well)[3]			
7,974 - 8,004	26	12	12
8,079 - 8,109	26	10	12
8,984 - 9,001	16	16	15
9,277 - 9,304	26	7	17
9,715 - 9,742	25	12	13
9,763 - 9,787	23	6	12
9,812 - 9,873	58	12	13
9,899 - 9,935	34	6	13
10,004 - 10,021	16	10	14
10,078 - 10,118	38	9	14
10,251 - 10,314	60	8	14
10,480 - 10,505	24	10	13
10,516 - 10,541	24	11	12
10,914 - 10,935	20	4	16
11,035 - 11,047	11	5	12
11,174 - 11,206	30	7	16
Net & means	**427/29**	**9**	**14**
BN 1-9 (Saddle Mountains well)[4]			
11,536 - 11,555	19	12	13
11,762 - 11,788	26	7	14
11,821 - 11,845	24	9	15
11,928 - 11,953	25	5	14
12,025 - 12,046	21	8	13
12,114 - 12,138	24	18	17
12,703 - 12,725	22	tr	14
Net & means	**161/23**	**8**	**14**

Interval (ft)	Net Porosity (ft)	Vclay (%)	Mean Porosity (%)
Bissa 1-29 (Whiskey Dick well)[2]			
5,464 - 5,480	16	28	17
6,128 - 6,140	12	26	17
6,143 - 6,172	29	28	16
6,630 - 6,653	23	29	15
6,781 - 6,798	17	26	13
6,893 - 6,912	19	25	13
6,955 - 6,977	22	25	13
7,187 - 7,207	20	28	13
7,210 - 7,227	17	28	12
7,285 - 7,296	11	28	12
7,409 - 7,437	28	28	12
7,965 - 7,990	25	26	10
9,457 - 9,486	25	29	10
9,930 - 9,948	16	13	11
Net & means	**280/20**	**26**	**13**
Yakima Minerals 1-33 (Rosa Dam well)[5]			
5,668 - 5,717	49	17	17
5,793 - 5,822	29	24	14
5,848 - 5,887	39	23	16
6,330 - 6,353	23	24	15
6,626 - 6,644	18	21	20
7,535 - 7,561	26	3	17
7,948 - 7,968	20	2	22
7,970 - 7,999	29	5	24
8,006 - 8,034	28	10	21
8,242 - 8,259	17	5	18
8,303 - 8,320	17	10	17
9,271 - 9,289	18	4	17
9,302 - 9,325	23	11	17
10,627 - 10,644	13	11	10
10,791 - 10,834	33	19	14
11,210 - 11,261	39	23	10
Net & means	**421/26**	**13**	**17**

Notes:

1. Quincy No. 1 Vclay interpretation from gamma-ray log (Shell Western E & P, Inc. 1987-1992). Porosity calculated from Compensated Neutron/Litho Density log crossplots. Thicknesses not corrected for dip.
2. Bissa 1-29 Vclay interpretation subject to considerable uncertainty owing to poor gamma-ray log character (Shell Oil Co., 1980-1988). Porosity from Compensated Neutron/Formation Density log crossplots. Dips corrected for 10 degree southwest to southeast dips above 9,000 feet and 30 degree mean west-southwest dips below that depth.
3. 23-35 BN thicknesses of sandstones between 7,974 and 8,109 corrected for a 29 degree west-southwest mean dip given on the mean-squared-dip dipmeter interpretation. The dip correction for sandstones below 9,300 feet depth is 19 degrees northwest. Mean dips are used because of considerable scatter in the interpreted dips. Vclay and mean porosity determined from Schlumberger VOLAN interpretation (Meridian Oil Co., 1989-1991).
4. BN 1-9 Vclay determined from gamma ray log (Shell Oil Co., 1980-1994). Thicknesses corrected for a mean dip of 7 degrees south-southeast. Porosity from Schlumberger Cyberlook and Compensated Neutron/Litho Density log crossplots.
5. Yakima Minerals 1-33 Vclay from poor-character gamma ray log (Shell Oil Co., 1980-1988). Thicknesses corrected for 6 to 12 degree southwest dips to 9,000 feet and 40 degree southwest dips below 10,000 feet. Porosity from Schlumberger Cyberlook and Compensated Neutron/Litho Density log crossplots.

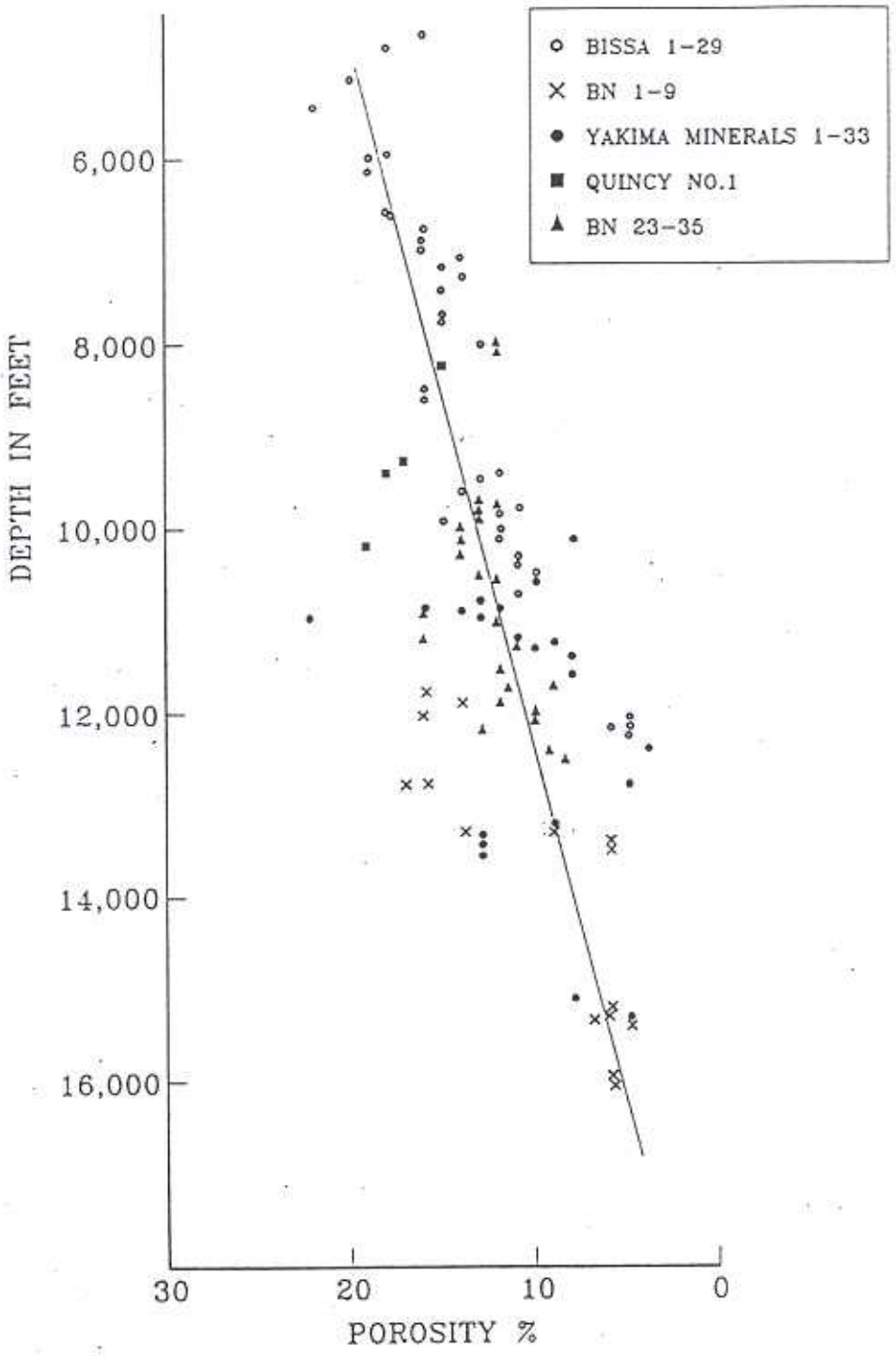

Figure 6. A porosity–depth plot of some Columbia Basin sandstones that are more than 10 feet thick (methods and references given on Table 4). All depths are referenced to kelly bushings. Only those sandstones having uniform and continuous porosity are included; the presence of claystones or other impermeable interbeds that can be resolved with wireline logging tools is considered to segregate a unit into multiple sandstone reservoirs for the purposes of this report. The line is a best fit to these data and depicts porosity degradation as a function of depth.

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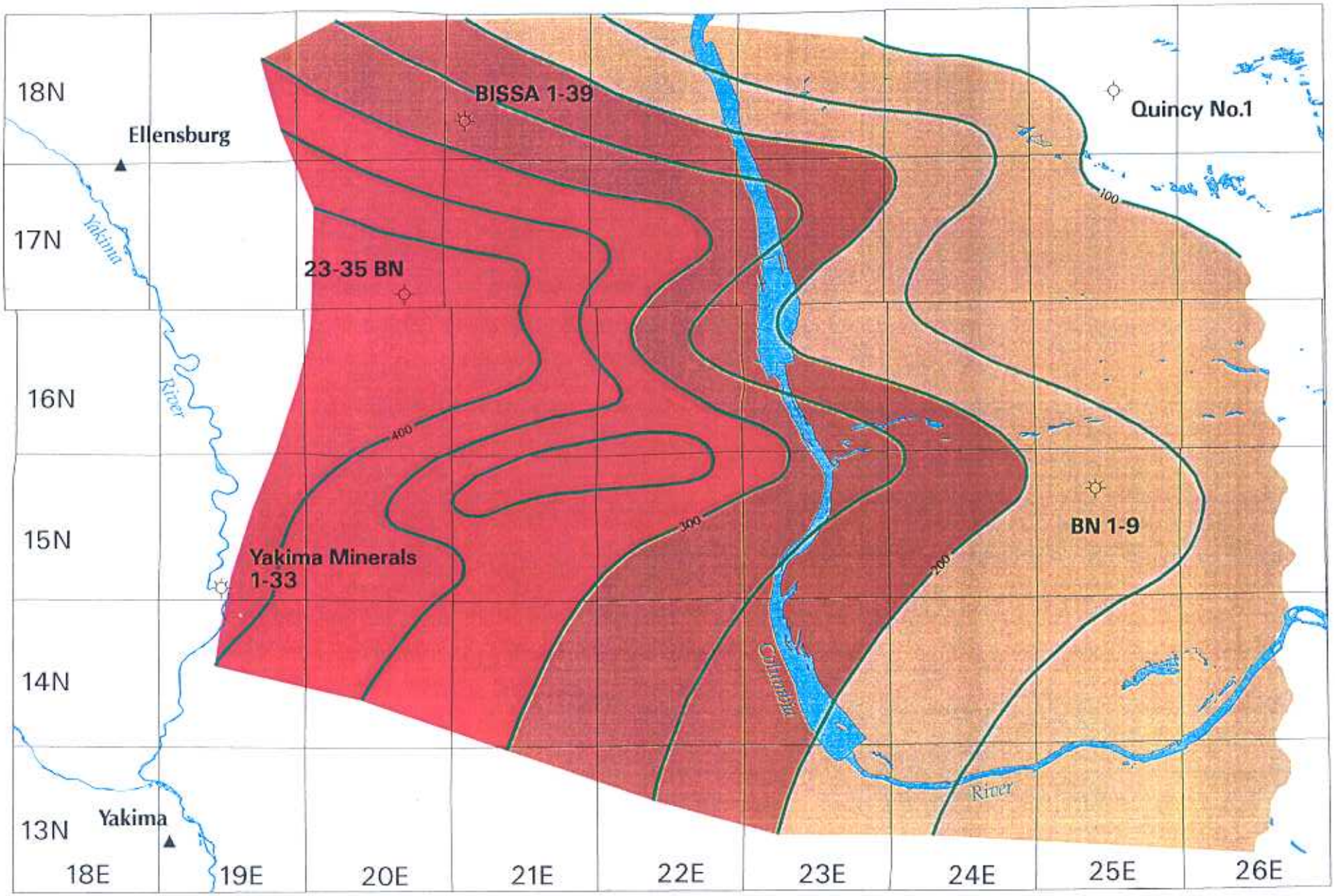
Figure 7. An isopach map showing the aggregate thickness of sandstone units that have porosity greater than 10 percent and individual unit thicknesses in excess of 10 feet as measured perpendicular to bedding (except for the Quincy No. 1, which is not dip corrected and may have less sandstone than depicted). The red and brown colors delineate the most favorable area for reservoir development. Contour interval = 50 feet. Data and interpretations methods summarized on Table 4. Formline contours are used except in the southeastern corner of the map where contours parallel the thickness of the Columbia River Basalt Group as extrapolated from thicknesses of the Grande Ronde Basalt (Reidel and others, 1989).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Ellensburg
Yakima
Yakima River
BISSA 1-39
23-35 BN
Yakima Minerals 1-33
Quincy No.1
BN 1-9
100
200
300
400
Columbia River

TABLE 5. Comparison of typical large Rocky Mountain oil and gas fields (Wyoming Geological Association, 1957) and Columbia Basin reservoir data.

OIL AND GAS FIELDS DATA

Glenrock, South Oil Field

Production[1] = 74.8 million barrels
Productive area = 6,600 acres
Sandstone 1 Thickness = 12 feet Porosity = 20%
Sandstone 2 Thickness = 7 feet Porosity = 14%
Sandstone 3 Thickness = 25 feet Porosity = 14%

Clareton - Mush Creek Oil Field

Production = 44.8 million barrels
Productive area = 70,000 acres
Sandstone 1 Thickness = 14 feet Porosity = 12%
Sandstone 2 Thickness = 8 feet Porosity = 17%

Beaver Creek Gas Field

Production = 877 billion cubic feet
Production depths 7,700 - 8,300
Productive area = 5,370 acres
Sandstone 1 Thickness = 40 feet Porosity = 13%
Sandstone 2 Thickness = 15 feet Porosity = 6%
Sandstone 3 Thickness = 45 feet Porosity = <25%

Baxter Basin Gas Field

Production = 273 billion cubic feet
Production depths 2,400 - 2,800 feet
Productive area = 5,000 acres
Sandstone 1 Thickness = 25 feet Porosity = 25%
Sandstone 2 Thickness = 35 feet Porosity = <25%

Worland Gas Field

Production = 419 billion cubic feet
Production depths = 7,000 - 10,000 feet
Productive area = 6,000 acres
Sandstone 1 Thickness = 47 feet Porosity = 17%
Sandstone 2 Thickness = 51 feet Porosity = 14%
Sandstone 3 Thickness = 18 feet Porosity = 13%
Average permeability = 10 md

COLUMBIA BASIN DATA

Yakima Minerals 1-33 Well

Depth = 10,000 feet
Sandstone 1 Thickness = 38 feet Porosity = 14%
Sandstone 2 Thickness = 60 feet Porosity = 14%
Sandstone 3 Thickness = 24 feet Porosity = 13%

23-35 BN Well

Depth = 9,800 feet
Sandstone 1 Thickness = 23 feet Porosity = 14%
Sandstone 2 Thickness = 58 feet Porosity = 13%
Sandstone 3 Thickness = 34 feet Porosity = 13%

Note:
Production data are from the Wyoming Geologic Survey and current as of April 1995.

TRAP

The Columbia Basin is structurally complex and poorly understood relative to most other basins. The complexity of folds and faults (Figures 2, 3, 9) is certain to result in an abundance of potential traps within the basin.

The proposed Yakima Firing Range Expansion Area lies within the Yakima fold belt where large anticlines, including the Manastash, Saddle Mountains, and Umtanum anticlines, are exposed at the surface (Fig. 2). These complex folds are mostly asymmetric, verge north except for a few south-verging fold segments, range from 3 to 6 miles across strike, and are from 75 to more than 100 miles long as measured along trend. The surface expression of these folds is similar in size and morphology to folds that entrap the giant oil and gas fields of Iran, Romania, western Alberta, and Wyoming. (See Figure 8.)

Contrary to published remarks, dipmeter interpretation indicates that structure in the Paleogene nonmarine sections penetrated in the BN 1-9 and Yakima Minerals 1-33 wells are disconformable with the overlying basalt. (See Notes on Table 4). The same may be true of the 23-35 BN. Therefore, surface structure may mimic the subsurface. Mapping by Bentley (1980) and Swanson and others (1979) suggests that trap areas within the fold belt could range from 3,000 to 25,000 acres if sub-basalt structure mimics basalt structure everywhere in the central portion of the basin. This relation is observed on reflection seismic data from some other Washington basins.

There are several competing theories for the origin of Yakima fold belt anticlines. Two major models are decollement thrusting and oblique or strikeslip faulting.

Many geologists have observed the dominant north vergence, fold spacing, and thrust displacement of faults at the surface and conclude the Yakima fold belt is a decollement thrust belt. (See Campbell, 1989.) The decollement surface is thought to be the base of the basalt. Therefore, it is possible that these anticlines fold only the basalt and not older strata. Basalt at Cleman Mountain is clearly detached from underlying Paleogene strata (Campbell and Reidel, 1991).

Similarly, it is likely that other, potentially productive anticlines and faults deform the Paleogene nonmarine rocks and have no manifestation in the basalt or at the surface. While the decollement thrust model is yet to be tested, some lines of evidence suggest this model may not be valid for all of the Yakima fold-belt structures:

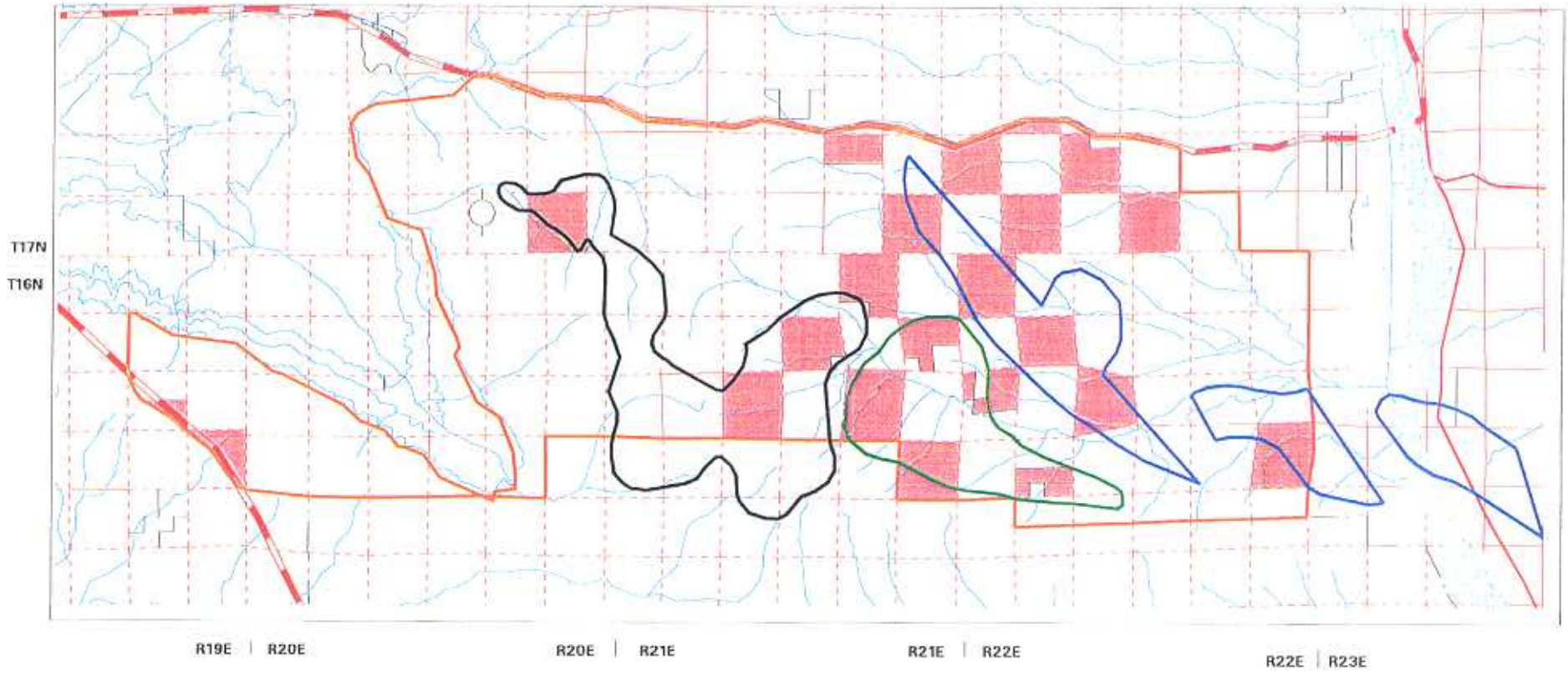
(1) Detailed basalt chemistry shows with some certainty that no repeated section is present in the Rattlesnake Hills No. 1, BN 1-9, Bissa 1-19, 23-35 BN, or Quincy No. 1, wells, indicating that these wells did not cut thrust faults (S. P. Reidel, Westinghouse Hanford, oral commun., 1995). Reidel observes that the 1-10 Darcell well did cut a fault in the Grande Ronde Basalt.

(2) The folds and faults have various vergence.

(3) Campbell (1989) outlines a history of sedimentation across the Hog Ranch–Naneum Ridge (Figure 2) wherein the ridge crest is a pre-Paleogene highland, a stratigraphically thickened area in the middle to upper Eocene, a thin during the Oligocene, and, finally, a highland during the middle Miocene. This pattern of stratigraphic/topographic reversal is typical of oblique or strikeslip terrains, but not of decollement thrust belts.

ON FOLLOWING PAGE

Figure 8. A comparison of the areas that would be condemned for the Yakima Firing Range Expansion Area with some large Rocky Mountain oil and gas fields (overlay). Glenrock South [black] is a stratigraphic trap located directly north of a major reverse fault; Beaver Creek [green] is a typical structural dome; and Baxter Basin [blue] is trapped by a series of faults (Wyoming Geological Association, 1957). These fields are good analogues of the types of accumulations anticipated in the Yakima fold belt. The field outlines have been arranged to overlay the map of condemned lands in a pattern that is concordant with known aspects of the geology of the Manastash and Saddle Mountains anticlines.



Legend

- Condemned DNR Land
- Approximate Boundary of Expansion Area
- South Glenrock Oil Field outline
- Beaver Creek Gas Field outline
- Baxter Basin Gas Field outline

Extreme care was used during the compilation of this map to insure accuracy. However, due to changes in ownership and the need to rely on outside information, the Department of Natural Resources cannot accept responsibilities for errors or omissions, and, therefore, there are no warranties which accompany this material.

WASHINGTON STATE DEPARTMENT OF
Natural Resources

Jennifer M. Belcher - Commissioner of Public Lands
Kaleen Cottingham - Supervisor
Resource Planning and Asset Mgmt. Div.

August, 1995

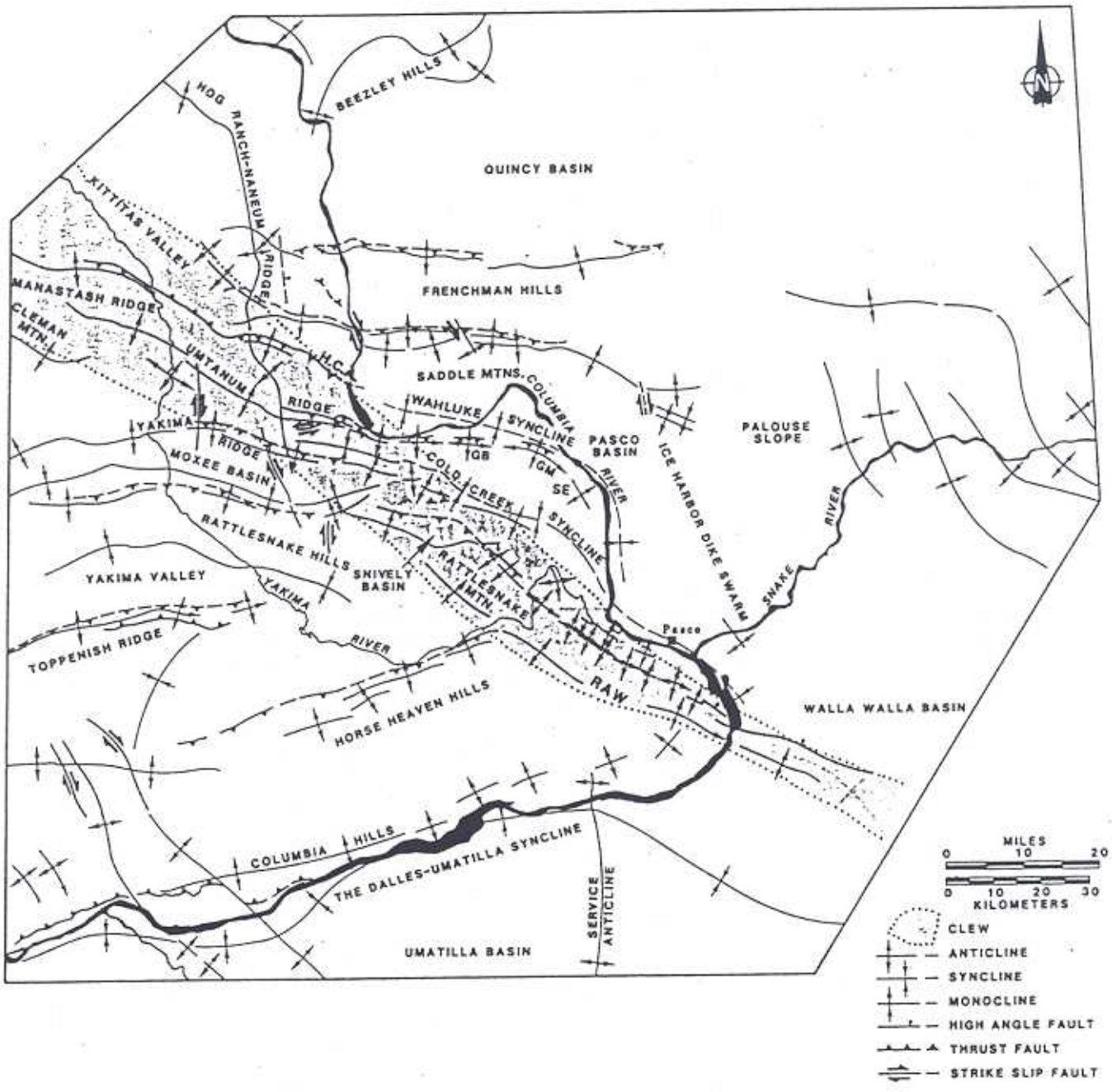


Figure 9. Major faults and folds in the central part of the Yakima fold belt and the western part of the Palouse (From Reidel and Campbell, 1989. Used with permission.)

(4) Seismic data (Jarchow, 1991) and well data (Campbell and Reidel, 1994) do not show the regional wedge of strata that thins away from a thrusted hinterland toward a thrusted foreland. These wedges characterize thrust belts.

(5) The regional "fan pattern" of folds in the northwestern Columbia Basin (Reidel and Campbell, 1989) has not been observed in other thrust belts.

Several lines of evidence are consistent with oblique-slip (see Lingley and others, 1994) or strikeslip faulting in the basin. These include lacustrine rocks, the rhombochasm morphology of the Entiat graben, the aforementioned uplift-down drop stratigraphic relations, some strikeslip focal mechanisms for recent Columbia Basin earthquakes, and the fact that many of the faults steepen with depth (Reidel and Campbell, 1989).

However, Reidel and Tolan (1994) make an equally strong argument that the Olympic-Wallowa lineament, which includes part of the Yakima fold belt, has not had significant strikeslip movement during the last 16 M.Y., the time period during which the folds grew (Reidel, 1984). However, it stands to reason that the Olympic-Wallowa lineament may not share a cogenetic relation with other Yakima fold belt structures because it cuts across a much larger region.

These arguments could easily be resolved with high-quality seismic data, but prior to 1992, there was no definitive, yet inexpensive means of mapping deeper structure in the basin. Relatively inexpensive prospecting techniques, including interpretation of gravity, magnetic, and electromagnetic data, failed to yield prospect-scale information owing to limited resolution of these tools.

However, recent experimental seismic work described above using very large energy sources and special refraction/reflection processing, has allowed Jarchow and others (1991, 1994) to map the base of the basalt and crystalline basement with precision. This technique could be used to produce maps of the entire basin, and it is likely that these products could be used interactively with conventional or 3-D seismic reflection surveys.

POTENTIAL RESERVES, LEASING, AND ROYALTIES

The most recent National Resource Assessment, undertaken by staff of the U.S. Geological Survey (Gautier and others, 1994), suggests that the Columbia Basin holds sufficient promise to encourage aggressive exploration and leasing in the future.

The U.S. Geological Survey estimated that a median of 10 and a maximum of 100 gas accumulations remain undiscovered in the Columbia Basin (Tennyson, 1994). They calculate that a very large accumulation (500 BCF) could be discovered in the basin. This analysis was performed without access to detailed reservoir data contained in Table 4. These data would have led to a conclusion that much larger accumulations could exist (M.E. Tennyson, U.S. Geological Survey, Denver, oral commun., 1995).

Reserve estimates published in 1986 by Lingley and Walsh continue to provide a reasonable picture of the basin's potential. The probability of a commercial discovery of 40 billion to 1 trillion cubic feet of gas remains comparable to that for other frontier basins worldwide. Data and assumptions used in the 1986 estimate are given in Table 6.

During the initial phases of exploration of frontier basins, mineral rights leases are let for minimal amounts and large acreage positions are developed by individual companies. Following encouragement in the form of good shows or aggressive wildcat drilling, lease bonuses typically range from $25 to $120 per acre. As the basin matures, leases in prospective areas can exceed $500 per acre.

The current depressed gas market will not last. In the United States, demand for energy is rising and about half of our domestic petroleum has already been consumed. We are currently importing a record amount of oil. Even if alternate sources of fuel energy are developed, natural gas will continue to have value as an important petrochemical feedstock used mainly in hydrogen, methanol, and ammonia synthesis (Kroschwitz and Howe-Grant, 1991).

In the event of a natural gas discovery, the income generated for the mineral rights owner would be significant. The probability of a commercial discovery appears to be similar to that in other frontier basins (about 1 in 16), if not higher. (The probability is non-zero because gas has already been produced at the Rattlesnake Hills Field.) In the case of commercial production, the mineral rights owner would earn a $1/8^{th}$ royalty income on all production from that land. For example, three wells producing from a hypothetical Columbia Basin gas field might generate more than $1,500,000 during the first ten years of production. (It is assumed that each well would flow 2,500 MCFGPD because gas fields developed in the Columbia Basin would have to be highly productive in order to recoup drilling costs. Other assumptions include annual decline of 0.30, a gas price of $1.50/MCF, 640-acre spacing, and transportation charges paid by the operator.

The mineral rights owner would also benefit from other new technology. For example, direct gas detection or basin-centered-gas development methods may allow explorationists to target much smaller accumulations and realize greater profit. In addition to conventional gas fields, the basin-centered deep gas play has potential to hold 11 billion cubic feet of gas per section (Law, 1994). Such reserves could provide significant impetus for continued exploration and leasing long after conventional gas accumulations or the potential to discover conventional gas accumulations have been exhausted.

Other Assessments

The following are published comments by petroleum professionals and scientists who have studied aspects of the petroleum potential of the Columbia Basin.

> "Shell has paid millions of dollars in leasing bonuses and annual lease rentals to a large number of Washington landowners covering approximately two million acres of land. This exploration activity has taken place and these benefits have been enjoyed at a time when the oil and gas industry has been experiencing, and continues to suffer from, one of the worst economic periods in its history, a time when major and independent oil and gas companies are drastically reducing or suspending exploration commitments in other wildcat and producing regions across the county." (Shell Western Exploration and Production, Inc.: Official statement read into the record of the Washington Oil and Gas Conservation Committee, April 30, 1987)
>
> "The second half of 1986 and the first half of 1987 have seen a relatively high level of exploration and leasing activity in the Columbia Basin." "....most of the basin has been already leased." (Faley, 1987)
>
> Arco characterizes shows from wells adjacent to the Firing Range as "excellent" (Withers and others, 1994)

"We do not currently have an estimate for amounts [of natural gas] in only the area being condemned, although it appears that the condemnation area lies in a particularly promising part of the play based on the locations of exploratory wells drilled in the 1980's." (M. E. Tennyson, USGS, Denver, Colorado, letter to John Holm and Sheldon Shuff dated October 17, 1994)

"If Shell's vibroseismic surveys can "see through" the basalt and determine the geometry of pre-basalt structure, hydrocarbons could be discovered in vast quantities in the Columbia Basin". (Bentley, 1987)

"The potential for oil and gas and coalbed methane is rated high (H/B high potential based on indirect evidence)." "Under the mineral resources most likely to be developed in the proposed Expansion area in the foreseeable future are leasable natural gas and coalbed methane. These are leasable resources and not included in the withdrawal application." (Ketrenos, 1993)

"The play [northwest Columbia Basin] is considered to have a very high probability of at least a few and possibly many, small gas accumulations, and a lower probability of large gas accumulations." (Tennyson, 1994)

"Based on preceding analysis of past and current oil and gas activities and trends, the following is a description of the reasonably foreseeable oil and gas exploration and development activity anticipated in the Spokane RMP area over the next 10 to 15 years. [:] Future exploration will most probably occur, as in the past, throughout the Columbia Basin and east-central Cascade Range with wells depths probably continuing in the 10-20,000 ft. range. These exploratory wells will better delineate the boundaries of gas occurrences and may possibly result in the discovery of a new field over the next fifteen years." (U.S. Bureau of Land Management, 1992)

Table 6. Columbia Basin possible gas-in-place data and assumptions.

Reservoir at	5,000 ft	10,000 ft	14,000 ft
Temperature (@ 40°C/km)(degrees R)	628	738	826
Z	0.75	0.85	1.00
Pressure (psi)	2,100	4,500	8,680
B_g (scf/cu ft)	150	240	370
Porosity (%)	18	12	8
Thickness (ft)	28	27	25
Number of pay zones	3	3	3
Mean areal extents (from Bentley, 1980)			
Mean fault traps (ac)	11,000	11,000	11,000
Mean largest 25% fault traps (ac)	25,000	25,000	25,000
Mean domes (ac)	6,000	4,000	3,000
Mean largest 25% domes (ac)	8,000	5,000	3,000
S_w (%)	65	65	65
Net-to-gross pay (%)	80	80	80
Fill-to-spill (%)	80	80	80

Conclusion

In the reasonably foreseeable future, the writer believes that aggressive exploration will take place in the northwestern Columbia Basin. Exploration is likely to be centered along favorable trends of structural geology, proven gas-generative source rocks, good geothermal gradients, excellent shows during production tests, and thick reservoir development on and near the Yakima Firing Range Expansion Area. The probability of a giant gas discovery on these lands is comparable with that of other frontier basins, and exceeds that of most mature provinces.

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