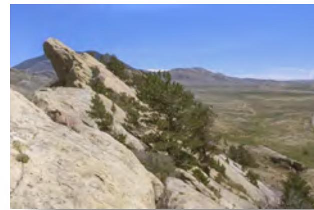
Chapter 10

The Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province



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By Thomas M. Finn, Ronald C. Johnson, and Stephen B. Roberts

Chapter 10 of
Petroleum Systems and Geologic Assessment of Oil and Gas in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah
By USGS Southwestern Wyoming Province Assessment Team

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The Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province

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Abstract

An assessment was made of the amount of gas in the Mesaverde–Lance–Fort Union Total Petroleum System in the Southwestern Wyoming Province that has the potential for additions to reserves in the next 30 years. The Total Petroleum System was divided into four assessment units by using variations in thermal maturity; the Mesaverde–Lance–Fort Union Continuous Assessment Unit, the Mesaverde Coalbed Gas Assessment Unit, the Fort Union Coalbed Gas Assessment Unit, and the Mesaverde–Lance–Fort Union Conventional Assessment Unit. The Continuous Assessment Unit is estimated to contain a mean of 13.635 trillion cubic feet of gas and 613.6 million barrels of natural gas liquids, the Mesaverde and Fort Union Coalbed Gas Assessment Units are estimated to contain a mean of 27.3 and 80.8 billion cubic feet of gas respectively, and the Conventional Assessment Unit is estimated to contain a mean of 2.3 million barrels of oil, 320.2 billion cubic feet of gas and 14.4 million barrels of natural gas liquids that have the potential for additions to reserves in the next 30 years.

Introduction

The Mesaverde–Lance–Fort Union Composite Total Petroleum System (TPS) is a predominantly gas-prone system within the western part of the Southwestern Wyoming Province (fig. 1), west of the pinch-out of the overlying Lewis Shale. This TPS, herein referred to as the Composite TPS, is designated number 503706, encompasses about 8,410 mi^2 of the western part of the Southwestern Wyoming Province, and includes much of the Green River and Hoback Basins and Moxa arch. The Composite TPS is considered here as one total petroleum system because all of the units were deposited in a nonmarine continental setting and contain similar gas-prone source rocks, and because there is no regional seal within the entire stratigraphic succession to inhibit the vertical migration of gas. To the east, where the Lewis Shale is present, the same stratigraphic interval is subdivided into three total petroleum systems in ascending order: the Mesaverde TPS (503705), the Lewis TPS (503707), and the Lance–Fort Union Composite TPS (503708). The Mesaverde–Lance–Fort Union Composite TPS is bounded on the west by the leading edge of the Wyoming thrust belt, on the east by the western limit of the Lewis Shale, and on the north and south by the limits of the Mesaverde Group and the Lance and Fort Union Formations in the Southwestern Wyoming Province (fig. 1).

The Composite TPS consists of, in ascending order, the Upper Cretaceous Rock Springs Formation, Ericson Sandstone, and Almond Formation of the Mesaverde Group; the Upper Cretaceous Lance Formation; the Paleocene Fort Union Formation; and the lower or main body of the Eocene Wasatch Formation (figs. 2–4). Along the west flank of the Moxa arch the term Adaville Formation is commonly applied to the rocks equivalent to the Rocks Springs Formation (fig. 3). The upper limit of the Composite TPS is placed at the base of the lowest regionally extensive lacustrine shale seal in the Wasatch or Green River Formation. In the Piceance Basin of western Colorado (Johnson and Rice, 1990) and in the Wind River Basin of central Wyoming (Johnson and Rice, 1993) gas compositions from above and below Tertiary lacustrine shales are chemically and isotopically distinct, suggesting that lacustrine shales act as seals inhibiting the vertical migration of gas in Rocky Mountain basins. The contact between the Mesaverde–Lance–Fort Union Composite TPS and the underlying Hilliard–Baxter–Mancos TPS was placed at the base of the Rock Springs Formation east of the Moxa arch, at the base of the Ericson Sandstone along the crest of the Moxa arch, where the Rock Springs Formation is missing, and at the base of the Adaville Formation along the west flank of the Moxa arch.

Acknowledgments

The authors wish to thank Rich Pollastro and Chris Schenk of the U.S. Geological Survey (USGS) National Oil and Gas Assessment team for discussions regarding the assessment of the Mesaverde–Lance–Fort Union Composite Total Petroleum System. We would also like to thank Troy Cook (USGS) for interpretations of production data and for providing graphs of EURs; Phil Nelson and Joyce Kibler (USGS) for providing drill-stem test and pressure data; Laura Roberts (USGS) for providing key maps and for providing burial-history and petroleum generation models; and Paul Lillis and Mike

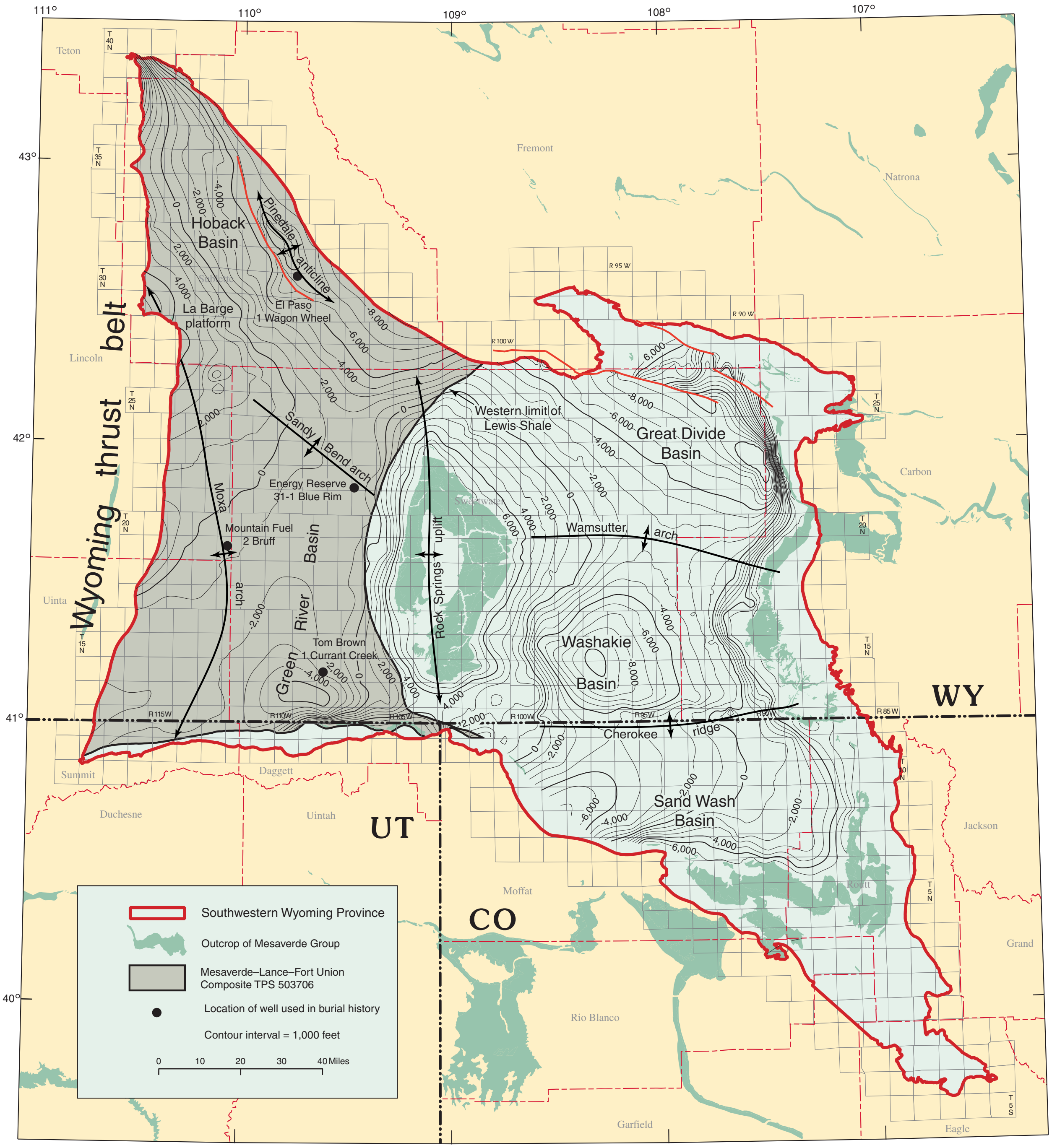

Figure 1. Distribution of Mesaverde Group outcrops and areal extent of the Mesaverde–Lance–Fort Union Composite Total Petroleum System in the Southwestern Wyoming Province. Structure contours drawn on top of Mesaverde Group. Contour interval is 1,000 feet. Locations of wells used to construct burial histories also shown.

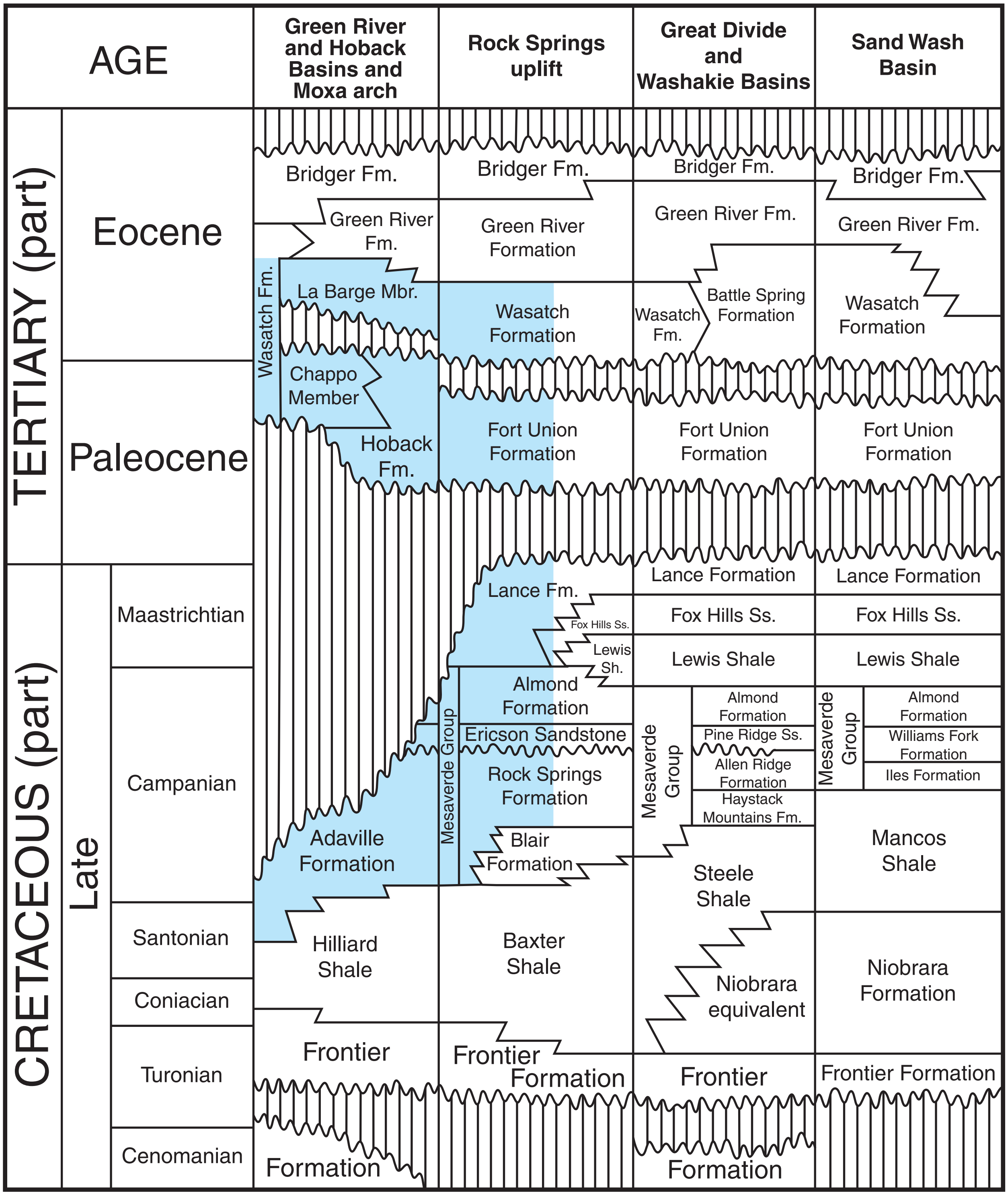

Figure 2. Generalized correlation chart for Cretaceous and lower Tertiary stratigraphic units in the Southwestern Wyoming Province. Mesaverde–Lance–Fort Union Composite Total Petroleum System shown in blue. Modified from Ryder (1988).

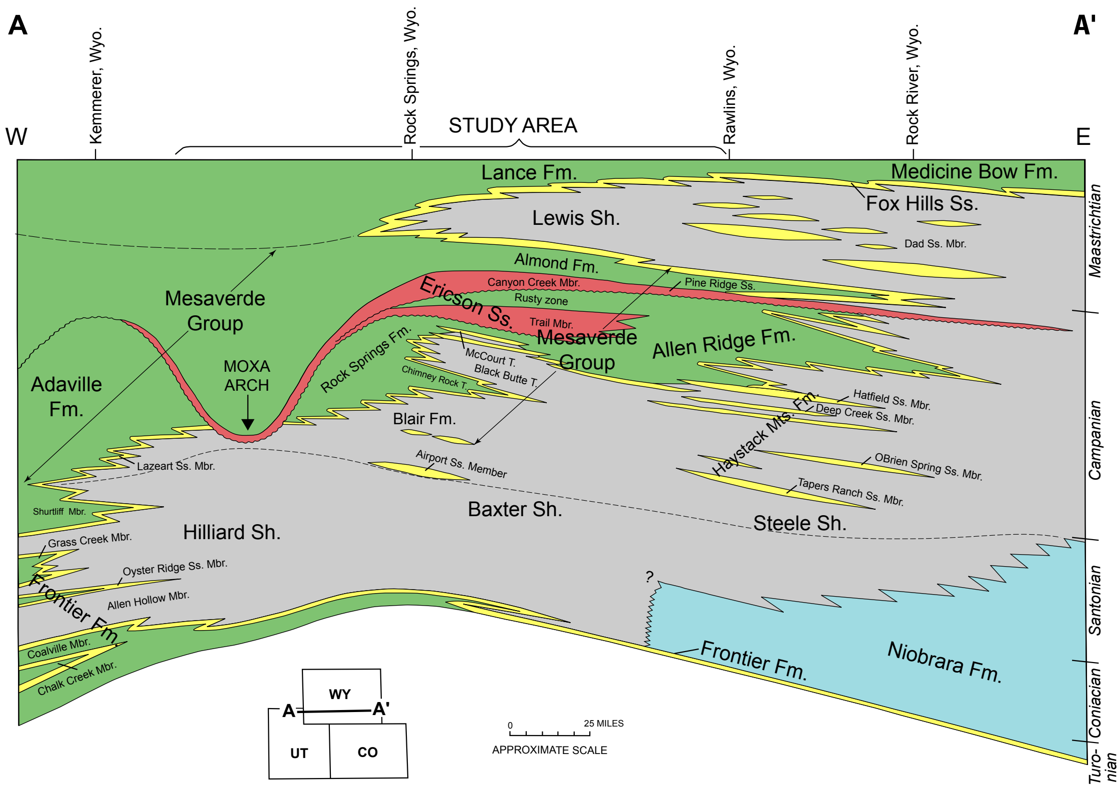

Figure 3. Generalized west to east cross section showing Upper Cretaceous stratigraphic units from northeastern Utah to southeastern Wyoming. Approximate limits of Southwestern Wyoming Province shown in brackets. Modified from Roehler (1990, his figure 7). Abbreviations used: Fm., Formation; Mbr., Member; Ss., Sandstone; Sh., Shale; T., Tongue.

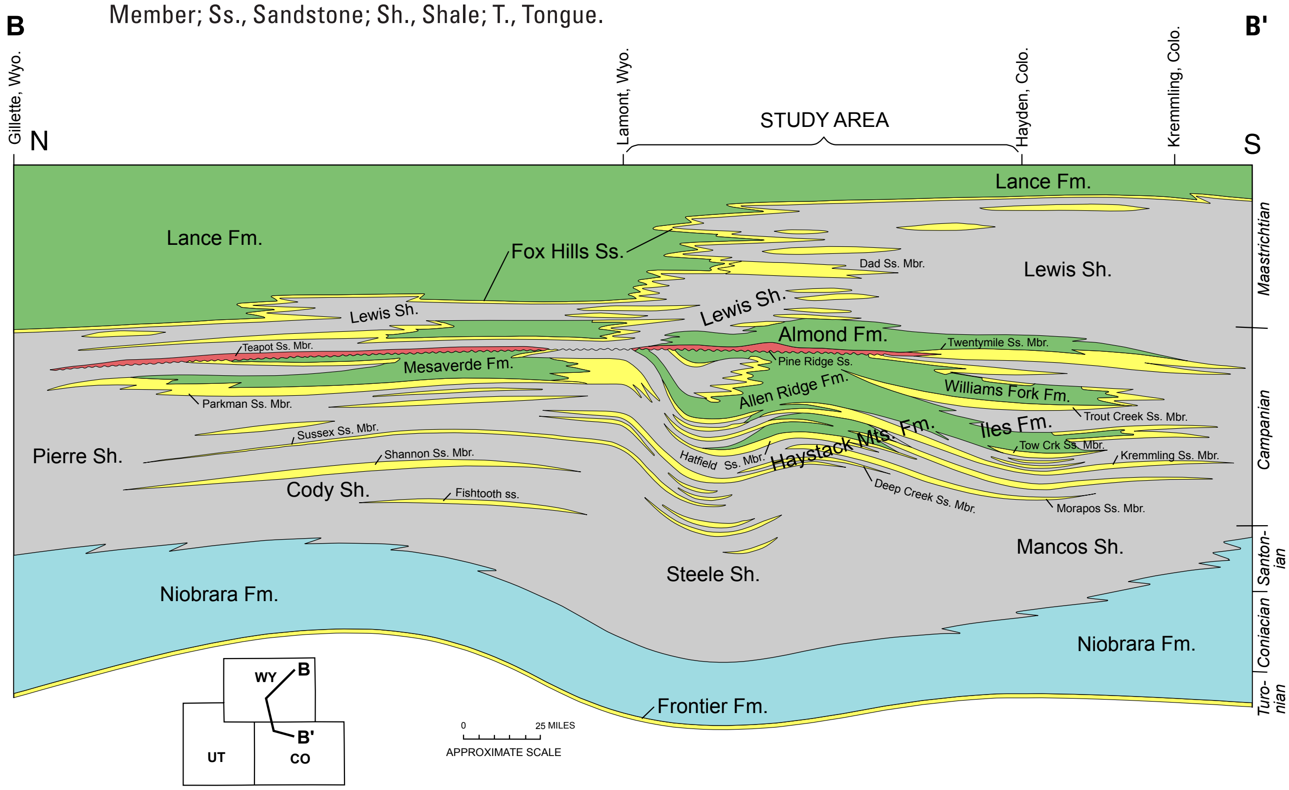

Figure 4. Generalized north to south cross section showing Upper Cretaceous stratigraphic units from northeastern Wyoming to north-central Colorado. Approximate limits of Southwestern Wyoming Province shown in brackets. Modified from Roehler (1990, his figure 9).

Lewan (USGS) for providing geochemical data and numerous discussions regarding organic geochemistry and source rocks. The manuscript was reviewed by Bob Hettinger and Chris Schenk (USGS) who provided many helpful comments and suggestions.

Hydrocarbon Source Rock

Coals and carbonaceous shales are presumed to be the primary source for gas and oil in the Composite TPS (Law, 1984); however, there is no effective seal between that TPS and the underlying Hillard–Baxter–Mancos TPS, and it is likely that some of the gas in the Composite TPS system came from marine shale source rocks in the underlying Hillard–Baxter–Mancos TPS. Coal is present mainly in the Rock Springs Formation, the Almond Formation equivalent, and the Fort Union Formation with only minor coal in the Ericson and Lance Formations (figs. 5–7). The Rock Springs Formation is progressively truncated toward the crest of the Moxa arch and is completely missing on the southern part of the crest of the arch (figs. 2 and 3). On the west flank of the arch, the term Adaville Formation is commonly applied to this interval. Rock Springs Formation coalbeds are largely confined to the area east of Moxa arch. Tyler and others (1995, their figure 29) measured from 0 to over 75 ft of coal in the Rock Springs Formation within the Composite TPS with the thickest accumulation northwest of the Rock Springs uplift. Total coal thickness in the Fort Union Formation is generally less than 20 ft along the margins of the Green River Basin but thickens to 60 to 140 ft along a north-south trend through the deep trough of the Green River Basin west of the Rock Springs uplift (Tyler and others, 1995). Coalbeds in the Fort Union are thickest and most laterally persistent, above and adjacent to fluvial channel sandstones along this trend with individual coal seams as much as 40 ft thick.

Source Rock Maturation

Vitrinite reflectance (R_o), measured from coal chips collected from drill-hole cuttings, was used to determine thermal maturity. Maps showing variations in R_o were constructed for three stratigraphic horizons within the Composite TPS: the base of the Rock Springs Formation of the Mesaverde Group and Adaville Formation, the top of the Mesaverde Group and equivalent strata, and the base of the Fort Union Formation and equivalent strata (figs. 8–10). Thermal maturities at the base of the Rock Springs and equivalent Adaville Formation, the stratigraphically lowest unit in the TPS, range from less than 0.6 percent R_o along the Rock Springs uplift in the east and the Moxa arch in the west, to more than 1.1 percent R_o in the deep trough of the Green River Basin and more than 2.0 percent R_o along the deep trough of the Hoback Basin (fig. 8). Thermal maturities at the top of the Mesaverde Group and equivalent strata range from less than 0.6 percent R_o along the Rock Springs uplift and Moxa arch to greater than 0.8 percent R_o in the deep trough of the Green River Basin and greater than 1.1 percent R_o along the deep trough the Hoback Basin (fig. 9). Thermal maturities at the base of the Fort Union Formation and equivalent strata range from less than 0.6 percent R_o along the Rock Springs uplift and Moxa arch to greater than 0.8 percent R_o along the deep troughs of the Green River and Hoback Basins (fig. 10).

Burial-history curves were constructed for four wells within the TPS: the Tom Brown no. 1 Currant Creek well (sec. 20, T. 14 N., R. 108 W.) in the deep trough of the Green River Basin, the Mountain Fuels no. 2 Bruff Unit well (sec. 16, T. 19 S., R. 112 W.) along the crest of the Moxa arch, the Energy Reserve Group no. 31-1 Blue Rim-Federal well (sec. 30, T. 22 N., R. 106 W.) along the Sandy Bend arch, and the El Paso no. 1 Wagon Wheel well (sec. 5, T. 30 N., R. 108 W.) on the Pinedale anticline just south of the deep trough of the Hoback Basin (fig. 1). The R_o profiles are published in Roberts and others (Chapter 3, this CD–ROM).

Roberts and others (this CD–ROM) applied time-temperature modeling to the burial reconstructions to estimate the timing of hydrocarbon generation for source rocks containing Type-III organic matter, whereas a kinetic model based on hydrous-pyrolysis experiments was used for the maturation of Type-II organic matter. Time-temperature modeling reconstructs the maturation of organic matter through time as a result of burial and heating.

Table 1 shows when critical vitrinite reflectance levels were achieved by Type-III organic matter by using time-temperature modeling. Critical R_o values listed include 0.5 percent, which is approximately where hydrocarbon generation begins (Waples, 1980), 0.8 percent, the approximate level where widespread overpressuring due to gas generation occurs in the Greater Green River Basin (Law, 1984), 1.1 percent, the approximate level where significant expulsion of hydrocarbons from coals begins (Levine, 1993), and 1.35 percent, where oil begins to crack into gas (Dow, 1977).

At the Wagon Wheel well on the Pinedale anticline south of the deep trough of the Hoback Basin (fig. 1), an R_o of 0.5 percent was reached at the base of the Mesaverde Group at 66 Ma, at the top of the Mesaverde Group at 58 Ma, and at the base of the Fort Union Formation at 45 Ma (table 1). An R_o of 0.8 was reached at the base and top of the Mesaverde Group at 58 Ma and at 45 Ma, respectively, and was never reached at the base of the Fort Union Formation. Only the base of the Mesaverde Group has reached the higher R_o values of 1.1 and 1.35 percent at 54 Ma and at 50 Ma, respectively (table 1).

In the Blue Rim well on the Sandy Bend arch separating the Hoback and Green River Basins (fig. 1), an R_o of 0.5 percent was reached at base of the Mesaverde Group at 54 Ma, at the top of the Mesaverde at 43 Ma, and at the base of the Fort Union Formation at 41 Ma. An R_o of 0.8 percent has been reached only at the base of the Mesaverde at 26 Ma.

The Tom Brown well in the deep trough of the Green River Basin (fig. 1) reached an R_o of 0.5 percent at the base of

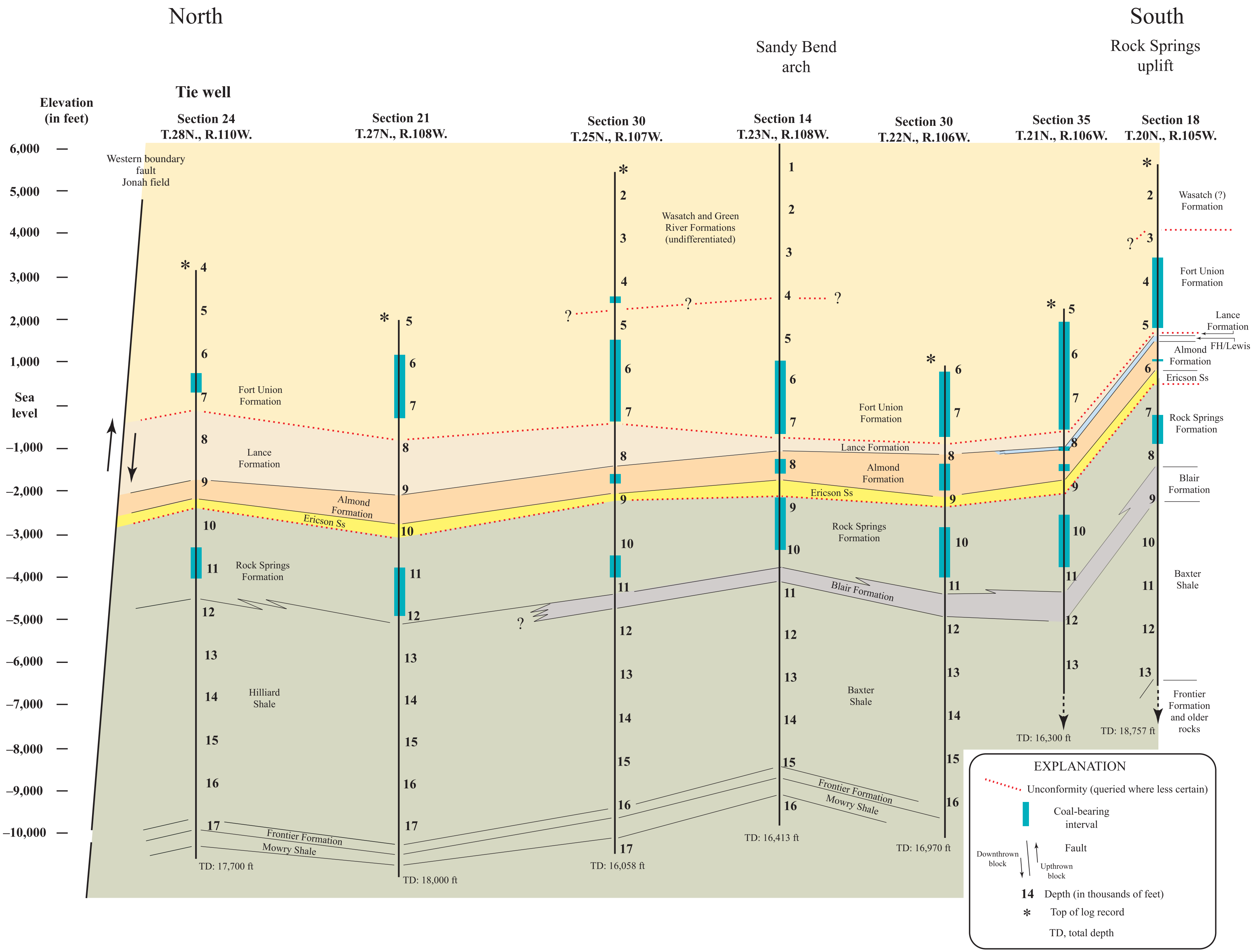

Figure 5. North to south cross section from Jonah field to the Rock Springs uplift showing stratigraphic relationships, unconformities, and coal-bearing intervals. At Jonah field, coal-bearing intervals do not occur in the gas-productive Lance Formation but only in the underlying Rock Springs Formation and overlying Fort Union Formation. FH is Fox Hills Sandstone. Location of section shown in figure 7. From Johnson and others (2004).

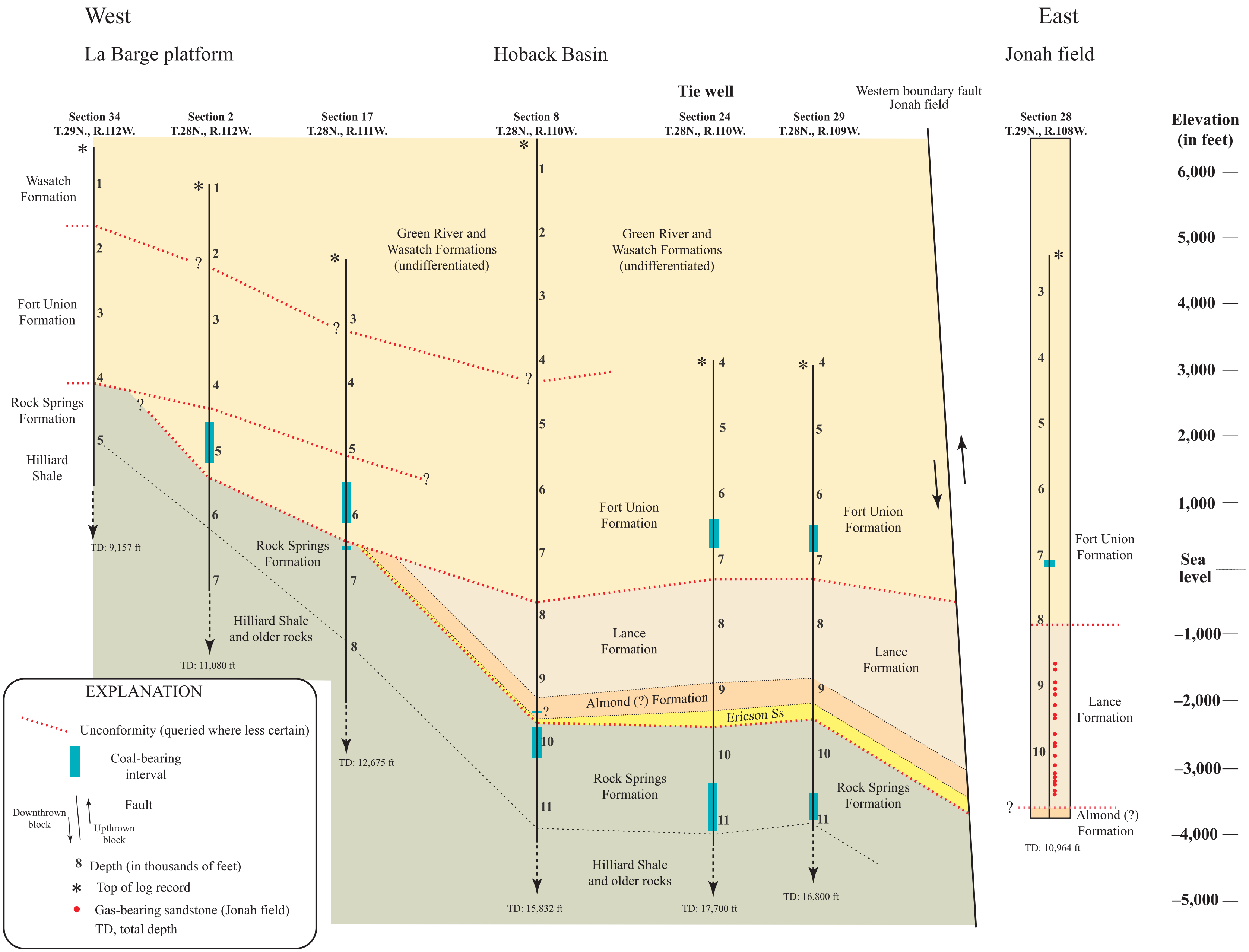

Figure 6. West to east cross section from the La Barge platform to Jonah field showing stratigraphic relationships, unconformities, coal-bearing intervals, and gas productive interval at Jonah field. Again, note the lack of coal-bearing gas source rocks in the productive Lance Formation at Jonah field. Location of section shown in figure 7. From Johnson and others (2004).

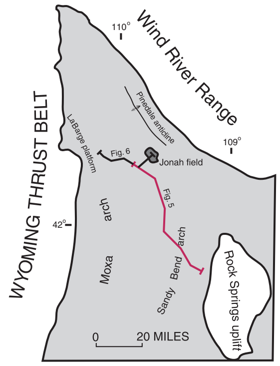

Figure 7. Index map for cross sections shown in figures 5 and 6.

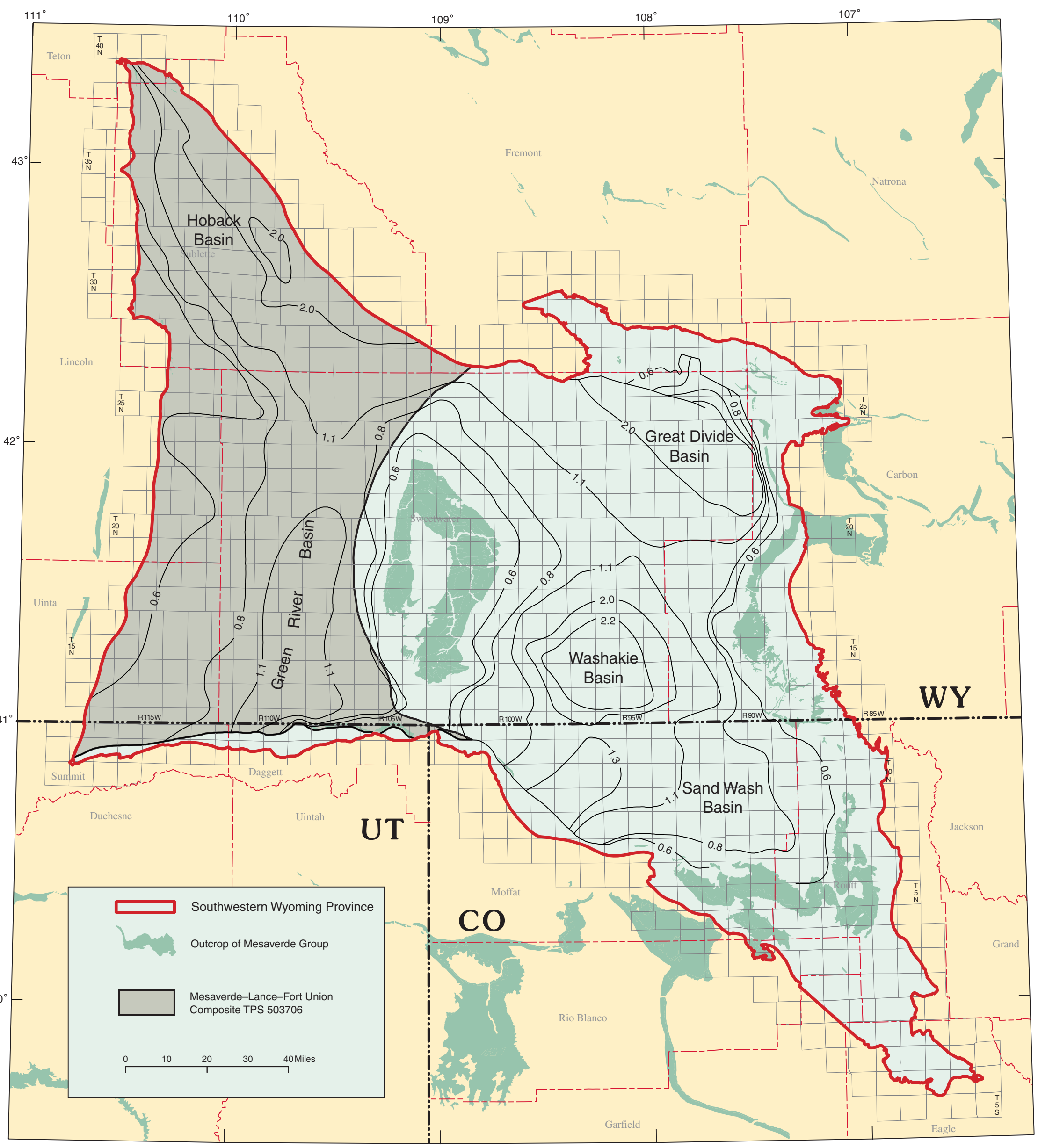

Figure 8. Variations in vitrinite reflectance at the base of the Upper Cretaceous Rock Springs Formation and equivalent strata, Southwestern Wyoming Province.

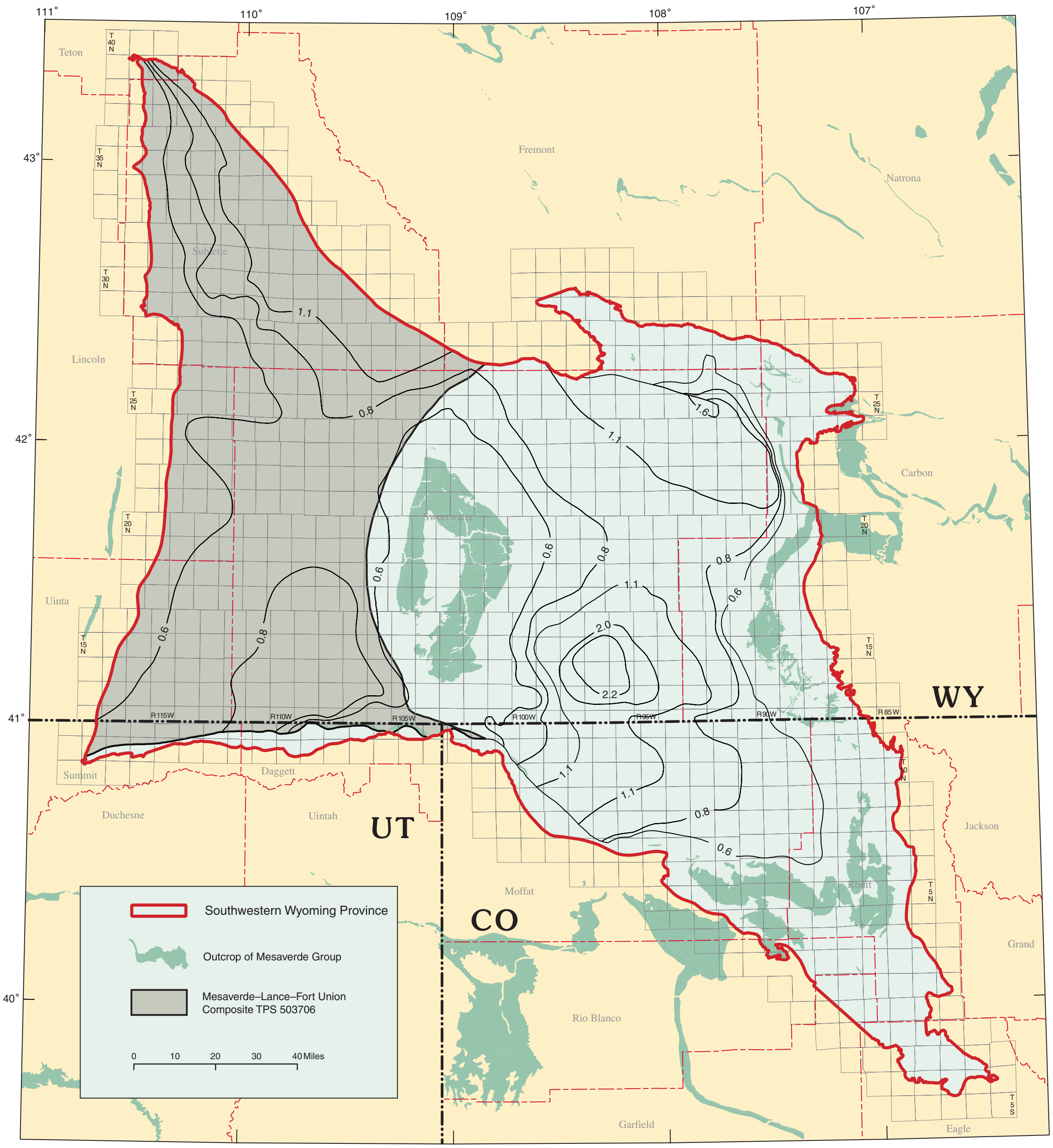

Figure 9. Variations in vitrinite reflectance at the top of the Mesaverde Group and equivalent strata, Southwestern Wyoming Province.

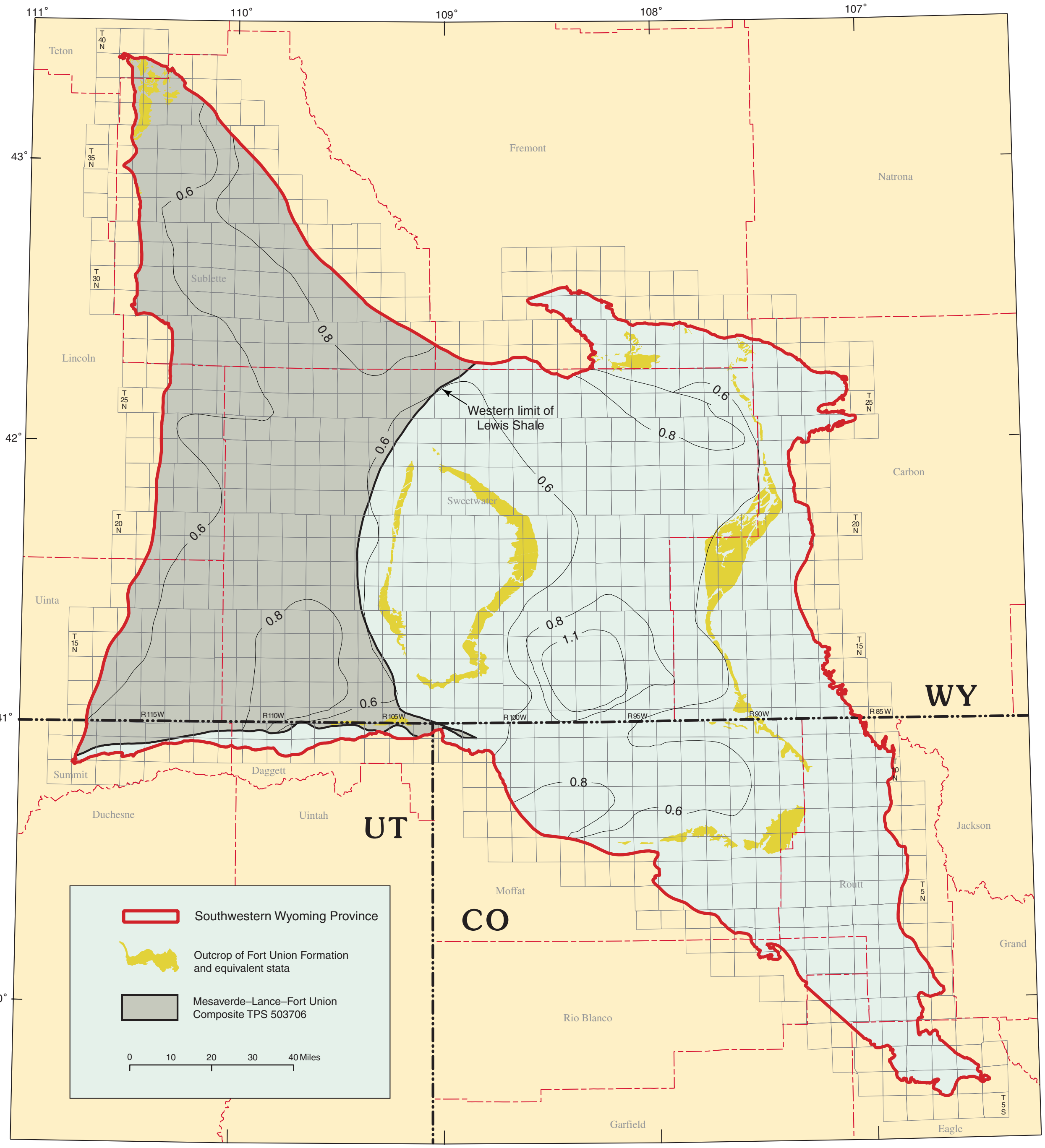

Figure 10. Variations in vitrinite reflectance at the base of the Paleocene Fort Union Formation and equivalent strata, Southwestern Wyoming Province.

the Mesaverde Group at 50 Ma, at the top of the Mesaverde Group at 43 Ma, and at the base of the Fort Union at 42 Ma (table 1). An R_o of 0.8 percent has been reached at only the base of the Mesaverde Group at 32 Ma.

The Mountain Fuel well along the crest of the Moxa arch has the lowest thermal maturities of the four wells, with an R_o of 0.5 percent reached at the base of the Mesaverde Group at 42 Ma, at the top of the Mesaverde at 39 Ma, and at the base of the Fort Union Formation, also at 39 Ma. An R_o of 0.8 percent has not been reached in the well at any of the aforementioned stratigraphic levels.

Kinetic modeling predicts timing and the amount of hydrocarbons generated by kerogen by using laboratory experiments such as hydrous pyrolysis. Table 2 summarizes the results of the kinetic modeling of Roberts and others (Chapter 3, this CD–ROM) for the four wells used for burial reconstructions previously discussed and shows the onset, peak, and end of oil and gas generation by Type-II organic matter. The model predicts oil generation at fairly low thermal maturities followed by gas generation at much higher levels of thermal maturity as oil is cracked to gas. The onset of oil generation in the four wells ranged from 61 to 40 Ma at R_o values of 0.65 to 0.68 percent (table 2). Peak oil generation was reached only at the Wagon Wheel well at 54 Ma and an R_o of 0.92 percent. The end of oil generation was reached in the Wagon Wheel well at 48 Ma at an R_o of 1.28 percent, while gas generation through the cracking of oil began in the well at 9 Ma at an R_o of 1.7 percent.

Hydrocarbon Migration Summary

Hydrocarbons can migrate laterally through persistent porous units or vertically through faults and fractures. Coals and organic-rich shales in the Mesaverde Group and Fort Union Formation are thought to be the principal source of oil and gas in both conventional and unconventional gas assessment units in the Composite TPS (Law, 1984). Figure 11 is a petroleum system events chart summarizing hydrocarbon generation and accumulation in the Mesaverde–Lance–Fort Union Composite TPS. The onset of gas generation by Type-III organic matter extends back to at least 66 Ma when gas generation began at the base of the Mesaverde Group in the Wagon Wheel well, the most thermally mature well analyzed. An R_o of 0.8 percent, which is used here as the beginning of peak gas generation by Type-III organic matter, occurred in the Wagon Wheel well about 58 Ma (table 1).

Coals have a substantial capacity to store hydrocarbon gases and liquids in micropores and cleats and to be adsorbed onto the molecular structure. Thus, large-scale migration from coalbeds into sandstone reservoir rocks would have begun when the capacity to store hydrocarbons had been exceeded. The stor-

Table 1. Million years before present that the vitrinite reflectance levels of 0.5, 0.6, 0.8, 1.1, 1.35, and 2.0 were reached in key wells in the Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province. [%, percent; NA, not applicable]

	Millions of years before present to reach the vitrinite reflectance levels listed below, in percent					
Selected wells	0.5%	0.6%	0.8%	1.1%	1.35%	2.0%
Energy Reserve Group no. 1-31 Blue Rim-Federal						
Base of Mesaverde Group	54	48	26	NA	NA	NA
Top of Mesaverde Group	43	30	NA	NA	NA	NA
Base of Fort Union Formation	41	17	NA	NA	NA	NA
Mountain Fuel no. 2 Bruff unit						
Base of Mesaverde Group	42	28	NA	NA	NA	NA
Top of Mesaverde Group	39	19	NA	NA	NA	NA
Base of Fort Union Formation	39	19	NA	NA	NA	NA
Tom Brown no. 1 Currant Creek						
Base of Mesaverde Group	50	46	32	NA	NA	NA
Top of Mesaverde Group	43	38	NA	NA	NA	NA
Base of Fort Union Formation	42	27	NA	NA	NA	NA
El Paso Wagon Wheel no. 1						
Base of Mesaverde Group	66	64	58	54	50	NA
Top of Mesaverde Group	58	55	45	NA	NA	NA
Base of Fort Union Formation	45	15	NA	NA	NA	NA

Table 2. Onset, peak, and end of oil and gas generation by Type-II organic matter for selected wells in the Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province using the kinetic model of Roberts and others (Chapter 3, this CD–ROM) [%, percent].

	Millions of years before present to reach the vitrinite reflectance levels listed below											
	Oil generation						Gas generation					
Selected wells	**Onset (Ma)**	**(%R_o)**	**Peak (Ma)**	**(%R_o)**	**End (Ma)**	**(%R_o)**	**Onset (Ma)**	**(%R_o)**	**Peak (Ma)**	**(%R_o)**	**End (Ma)**	**(%R_o)**
Mountain Fuel no. 2 Bruff unit												
Base of Mesaverde Group	40	0.68			0	0.85	No gas					
Tom Brown no. 1 Currant Creek												
Base of Mesaverde Group	42	0.65					No gas					
Energy Reserve Group no. 1-31 Blue Rim-Fed.												
Base of Mesaverde Group	41	0.66										
El Paso Wagon Wheel no. 1												
Base of Mesaverde Group	61	0.65	54	0.92	48	1.28	9	1.7				

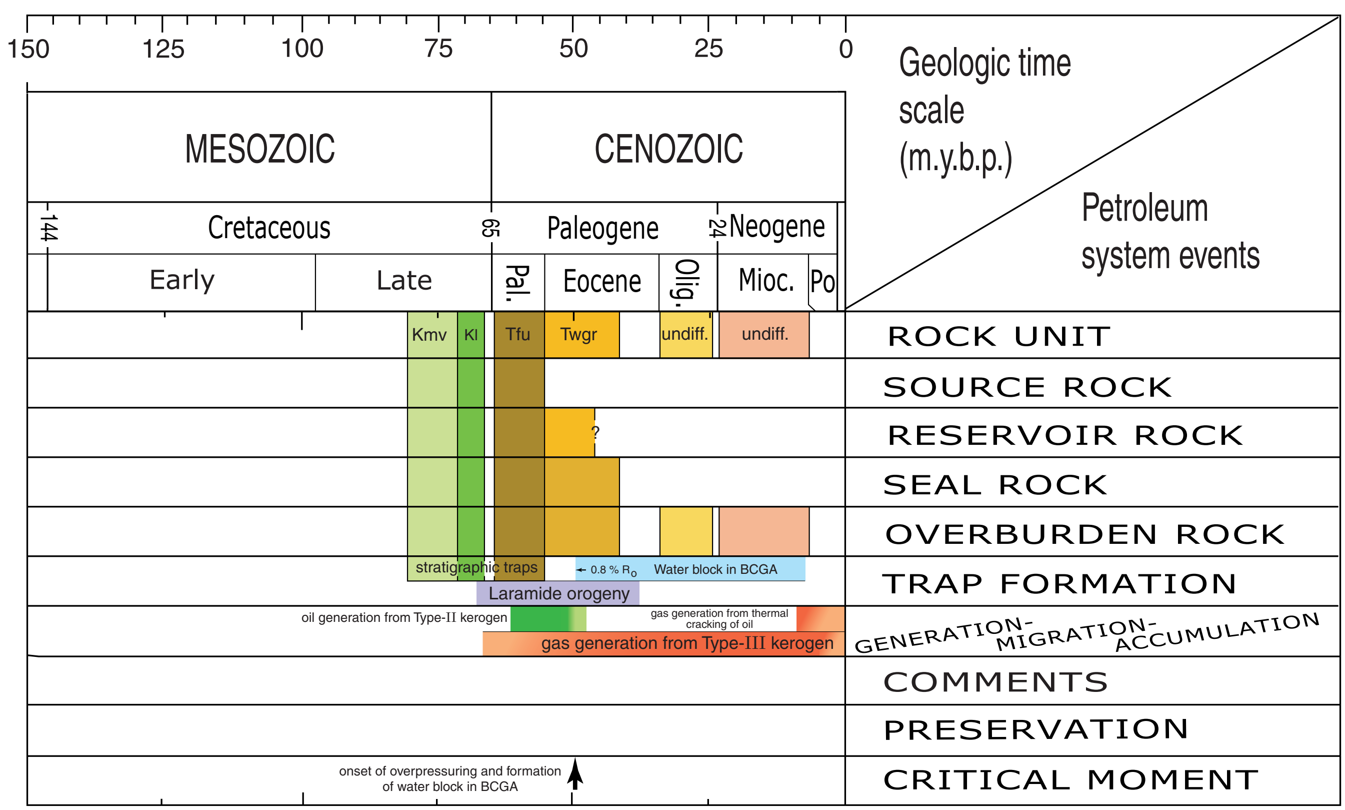

Figure 11. Petroleum system events chart showing interpreted timing of elements and processes related to hydrocarbon generation and accumulation in the Mesaverde–Lance–Fort Union Composite Total Petroleum System (AU 503706). Water block refers to hydrocarbon trapping by capillary seal. The timing of hydrocarbon generation is from Roberts and others (Chapter 3, this CD–ROM). Events charts modified from Magoon and Dow (1994). Kmv, Mesaverde Group; Kl, Lance Formation; Tfu, Fort Union Formation; Twgr, Wasatch and Green River Formations undivided; undiff., undifferentiated; Pal., Paleocene; Olig., Oligocene; Mioc., Miocene; Po, Pliocene; BCGA, basin-centered gas accumulation; R_o, vitrinite reflectance; m.y.b.p., million years before present.

age capacity for methane in coal decreases with increasing coal rank and temperature but increases with increasing pressure (Juntgen and Karweil, 1966; Meissner, 1984). Methane storage capacity will also vary for different types of coal. Levine (1991) suggests that the micropore structure in hydrogen-rich coals and kerogen may be plugged with oil, thus reducing the storage capacity for methane when compared with more vitrinite-rich coals. It is generally thought, however, that major expulsion of hydrocarbons begins at the onset of devolitalization (R_o 1.0–1.1 percent) when hydrogen to carbon (H/C) ratios in coalbeds turn sharply downward (Levine, 1993). A mass-balance approach, which calculates the amounts of water, carbon dioxide, and methane given off during coalification based on changes in H/C and oxygen to carbon (O/C) ratios, suggests that coals continue to generate methane to an R_o of at least 4.0 percent (Juntgen and Karweil, 1966). Laboratory pyrolysis experiments, which measure the amount of methane given off by coals during heating, also suggest that methane is generated by coals to at least an R_o of 4.0 percent (Higgs, 1986).

Garcia-Gonzalez and others (1993), in their study of the source-rock potential of coals in the Greater Green River Basin using coal petrography, vitrinite reflectance, anhydrous pyrolysis, and nuclear magnetic resonance, found that Almond Formation coals in the center of the Washakie Basin are in the oil window between an R_o of 0.47 and 1.45 percent at depths of between 4,000 and 12,000 ft, but evidence of expulsion of oil from Almond coals occurs only at depths of from 9,000 to 12,000 ft and at R_o levels of 0.90 to 1.45 percent.

The 1.1 percent R_o level was reached at the base of the Mesaverde Group, and thus the base of the Composite TPS, in only one of the four wells, the Wagon Wheel well on Pinedale anticline near the trough of the Hoback Basin at 54 Ma in the earliest Eocene (table 1). Thus, major hydrocarbon expulsion by coalbeds in the lower part of the Composite TPS probably began in early Eocene time in the deep trough of the Hoback Basin and spread into the deeper parts of the Green River Basin by the middle Eocene. At present, the 1.1 percent or greater R_o level occurs at the base of the Mesaverde Group throughout the deeper areas of the Hoback and Green River Basins (fig. 8). The deep trough of the Hoback Basin is the only area in the TPS where the top of the Mesaverde Group has attained an R_o of 1.1 percent or greater (fig. 9). Fort Union coals, with a maximum R_o of just over 0.8 percent (fig. 10), are probably not a significant source of gas found in sandstones in the Composite TPS but may contain coalbed methane deposits. The rate of hydrocarbon generation has decreased significantly during the last 5–10 m.y. due to regional uplift and downcutting; thus, migration of hydrocarbons has also slowed.

Garcia-Gonzalez and Surdam (1995) in a study comparing the hydrocarbon generation potential and expulsion efficiencies of coals and organic-rich shales in the Almond Formation found that organic-rich shales, which typically have less than 10 percent of the total organic carbon of coals, generate only about 10 percent of the oil and methane of coals with hydrous pyrolysis experiments. Expulsion of hydrocarbons out of shales, however, is much more efficient than out of coals because the hydrocarbons can migrate into the clay matrix and then out of the shale, whereas significant expulsion of hydrocarbons from coals only can occur once microfractures form. Thus, expulsion of gas from organic-rich shales might occur at lower thermal maturities than expulsion from coal, providing a source of gas at R_o levels of significantly less than 1.1 percent.

Gas expelled from coals and organic-rich shales migrated into nearby, low-permeability sandstone beds in the Mesaverde Group, initiating the development of a basin-centered gas accumulation. Migration was probably aided by fractures that formed as pressures increased and eventually exceeded fracture gradients during active gas generation and expulsion. Some of this gas escaped into the overlying Lance and Fort Union Formations, charging both conventional and low-permeability reservoirs in these units. Migration would have been largely vertical through faults and fractures in the thick intervals with mainly lenticular fluvial reservoirs in the TPS, such as the upper part of the Rock Springs Formation and the Lance and Fort Union Formations, but lateral migration could have occurred along blanketlike marginal marine sandstones in the Almond Formation, the lower part of the Rock Springs Formation, and the regionally extensive Ericson Sandstone in the upper part of the Mesaverde Group.

Extensive vertical migration of gas out of coaly source rocks through overlying fluvial rocks has been documented in several Rocky Mountain basins (Johnson and Rice, 1990; Rice and others, 1992; Johnson and others, 1994; Johnson and Rice, 1993; and Johnson and Keighin, 1998). Vertical migration is largely stopped at thick lacustrine shale intervals such as the Waltman Shale Member of the Paleocene Fort Union Formation in the Wind River Basin of Wyoming (Johnson and Rice, 1993; Johnson and Keighin, 1998) and the Eocene Green River Formation in the Piceance and Uinta Basins of Colorado and Utah (Johnson and Rice, 1990; Rice and others, 1992). Although isotopic analyses are not available for the Southwestern Wyoming Province, it is likely that vertical migration occurred through the thick fluvial intervals here as well. The lowest lacustrine shale in the Wasatch or Green River Formation in the Mesaverde–Lance–Fort Union TPS probably also acts as a regional seal, inhibiting the vertical migration of gas and thus marking the top of the TPS.

Hydrocarbon Reservoir Rocks

Reservoir rocks are mainly fluvial sandstones, found throughout the Rock Springs, Adaville, Ericson, Lance, and Fort Union Formations and lower part of the Wasatch Formation, marginal marine sandstones in the Almond Formation and lower part of the Rock Springs and Adaville Formations, and coalbeds in the Rock Springs Formation, Almond Formation equivalent, and Fort Union Formation. Shorelines trended generally southwest to northeast across the Composite TPS and transgressed and regressed through a relatively narrow belt along this trend throughout much of the deposition of the Rock Springs Formation (Roehler, 1990), producing marginal marine sandstone reservoirs that are elongate in that direction. Coals were deposited landward of the shoreline; thus, the thickest coal accumulations also lie in a southwest to northeast belt extending across the TPS (Tyler and others, 1995, their figure 29).

Although the Mesaverde–Lance–Fort Union Composite TPS occurs west of the pinch-out of the Lewis Shale, marginal marine bar sandstones of the Almond Formation persist a considerable distance west of the pinch-out, and exploring for these bar sandstones has become an important new objective in the Composite TPS (Kovach and others, 2001). These bar sandstones, which are generally elongate parallel to the north-south-trending Lewis shoreline, are present only along the eastern margin of the Composite TPS.

The interval from the top of the Ericson Sandstone to the top of the Lance Formation is less than 1,000 ft thick in the Green River Basin and Moxa arch and is completely missing on the La Barge platform but thickens in the Hoback Basin toward the Wind River Range to over 5,000 ft (fig. 12). Paleocene rocks unconformably overlie the Upper Cretaceous section throughout most if not all of the Composite TPS; thus, the general lack of Maastrichtian strata could be the result of erosion as well as nondeposition. Work by DeCelles (1994) on the thrust belt in southwest Wyoming and northern Utah indicates that little thrusting occurred along this segment of the thrust belt during late Campanian and early Maastrichtian time. Thus the lack of Maastrichtian strata in these areas may in part be due to isostatic rebound in the foreland basin as the Sevier highlands to the west were being eroded during this quiescent tectonic period (Johnson and others, 2004). The tremendous thickening of the Lance Formation toward the Wind River Range indicates that the range was actively rising during Maastrichtian time, thrusting southwestward over the margin of the Hoback Basin, and creating a deep trough in the basin adjacent to the uplift.

Paleodrainages flowed generally eastward off of the Sevier highlands and toward the Maastrichtian seaway during Lance deposition. A major drainage system flowed southeastward along the deep trough of the Hoback Basin adjacent to the actively rising Wind River Range (Johnson and others, 2004). Smaller drainages flowed southwestward off of the Wind River Range and into this major drainage. Thus, fluvial sandstones in the Lance Formation in the Composite TPS should largely trend east to southeast.

The Fort Union Formation unconformably overlies older rocks throughout most if not all of the TPS. It averages about 2,000 ft thick in much of the Green River Basin and on the Moxa arch and thickens to more than 6,000 ft toward the trough of the Green River Basin just southwest of the Wind River Range (McDonald, 1972; Gries and others, 1992). A major trunk stream flowed through the trough of the Green River Basin. Tyler and others (1995) believed that this stream flowed northward from the Uinta Mountains, joining a southeast flowing stream that flowed along the trough of the Hoback Basin and then exited the Hoback Basin between the Rock Springs uplift and the Wind River Range. Tyler and others (1995) subdivided the Fort Union Formation west of the Rock Springs uplift into (in ascending order): the massive Cretaceous-Tertiary boundary sandstone, the lower coal-bearing unit, the basin sandy unit, and the upper shaly unit; the thickest and most persistent coals are in the lower coal-bearing unit.

The contact between the Fort Union Formation and overlying Wasatch Formation is difficult to pick throughout much of the Composite TPS (McDonald, 1972). Roehler (1992, p. D82), in a detailed measured section of Eocene rocks on the east flank of the Rock Springs uplift and east of the Mesaverde–Lance–Fort Union Composite TPS, describes the contact between the Fort Union and the Wasatch: "The Fort Union Formation contains abundant beds of carbonaceous shale and coal—the Wasatch Formation in this area does not." Farther to the west, on the southwest flank of the Rock Springs uplift, near the southeast corner of the Composite TPS, Kirschbaum (1987) was unsuccessful in his attempt to find a mappable contact between the Fort Union and overlying Wasatch Formation and arbitrarily placed the contact at the first occurrence of predominantly greenish mudstone about 100 ft above the highest coalbed. Kirschbaum (1987) attempted to find the Paleocene-Eocene contact using palynomorphs but no Eocene palynomorphs were ever identified. In this study, the upper contact of the Composite TPS is placed at the lowest significant lacustrine shale bed in the overlying Wasatch or Green River Formation that could act as a regional seal.

Hydrocarbon Traps and Seals

Lacustrine shales in the Wasatch and Green River Formations probably act as regional seals inhibiting the vertical migration of gas out of the Mesaverde–Lance–Fort Union Composite TPS and into the overlying Wasatch–Green River Composite Total Petroleum System (503709) (Chapter 3, Roberts, this CD–ROM). As previously stated, gas compositions from above and below similar Tertiary lacustrine shales in the Piceance Basin of western Colorado are chemically and isotopically distinct (Johnson and Rice, 1990). Shale and mudstone intervals within the TPS also act as local seals. A shale and mudstone interval in the upper part of the Lance Formation at Jonah field is thought to be critical to the trapping of gas (Warner, 1998). Lateral seals at Jonah field are formed by faults (Warner, 1998). The pinch-out of lenticular sandstones into shale and mudstone can also form lateral seals. The overall trapping mechanism for continuous-type accumulations, such as the continuous gas accumulation that occurs in the Mesaverde–Lance–Fort Union Composite TPS in the more thermally mature (R_o greater than 0.80 percent) parts of the TPS, is considered to be a capillary seal or water block, which

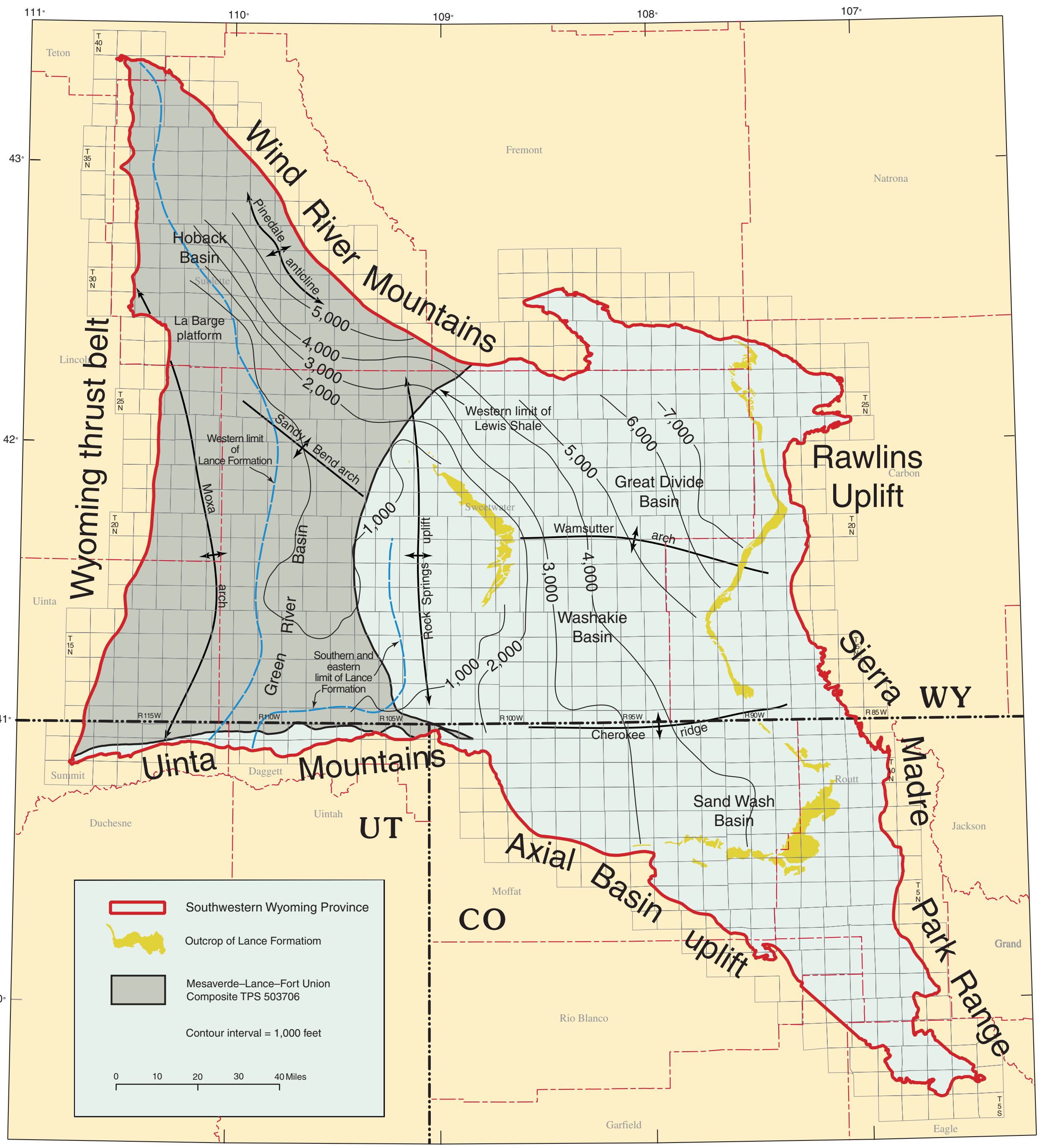

Figure 12. Isopach map showing approximate variations in thickness of Maastrichtian rocks, Southwestern Wyoming Province (from Johnson and others, 2004). The isopached interval consists of the Lance and Almond Formations west of the pinch-out of the Lewis Shale. Where the Lewis Shale is present, the isopached interval includes the Lewis.

develops in tight (low-permeability) gas-charged intervals (Masters, 1979).

Definition of Assessment Units

The Mesaverde–Lance–Fort Union Composite TPS is divided into four assessment units: (1) Mesaverde–Lance–Fort Union Continuous Gas Assessment Unit (AU) 50370661; (2) Mesaverde–Lance–Fort Union Conventional Oil and Gas AU 50370601; (3) Mesaverde Coalbed Gas AU 50370681; and (4) Fort Union Coalbed Gas AU 50370682. The Mesaverde–Lance–Fort Union Continuous Gas AU encompasses the deeper part of the Composite TPS where thermal maturities at the base of the Composite TPS are 0.8 percent R_o or greater (figs. 8, 13). The eastern boundary is the western limit of the Lewis Shale, which fairly closely follows the 0.8 percent R_o thermal maturity at the base of the Composite TPS. The Mesaverde–Lance–Fort Union Conventional AU encompasses the entire Composite TPS and overlies the Continuous Assessment Unit in the deeper parts of the Composite TPS (fig. 14). The coalbed methane AUs are defined as those areas where significant coal occurs in the TPS at depths of 6,000 ft or less. The Mesaverde Coalbed Gas AU is split into four areas: two on the west and southwest flanks of the Rock Springs uplift, one along the north flank of the Uinta Mountains, and one covering part of the La Barge platform (fig. 15). The Fort Union Coalbed Gas AU is split into four areas: two along the west flank of the Rock Springs Uplift and two along the Moxa arch and La Barge platform (fig. 16).

Assessment Results

Mesaverde–Lance–Fort Union Continuous Gas Assessment Unit (AU 50370661)

The Mesaverde–Lance–Fort Union Continuous Gas AU covers almost 3.5 million acres in the deeper areas of the Mesaverde–Lance–Fort Union Composite TPS, and the boundaries are defined by the thermal maturity level of 0.8 percent R_o or greater at the base of the Rock Springs Formation, the stratigraphically oldest unit in the assessment unit (fig. 13). The Conventional Assessment Unit overlies the entire area of this AU, and the contact between the Mesaverde–Lance–Fort Union Continuous Assessment Unit and the overlying Conventional AU cannot be uniquely defined. Instead, each oil and gas field within the boundaries of the continuous assessment unit was assigned to either the continuous or conventional assessment unit based on production characteristics. Two gas fields, Jonah and Pinedale, are included in the continuous gas assessment unit (fig. 13) whereas three oil fields and four gas fields, which exceeded the minimum field size of 0.5 million barrels of oil equivalent grown, were included in the conventional gas assessment unit (fig. 14). Jonah field is bounded on two sides by faults. Overpressuring within the field occurs at depths of from 2,500 to 3,000 ft less than outside the field, and it appears that vertical gas migration up faults and fractures is largely responsible for this anomaly (Warner, 1998; Bowker and Robinson, 1997). A thick, fine-grained fluvial interval in the upper part of the Lance Formation appears to act as a top seal (Warner, 1998, 2000). Warner believed that this seal was critical to the development of Jonah. Jonah has been described as both a “sweet spot” in the continuous accumulation (Bowker and Robinson, 1997; Law, 2002), the concept adopted here, and as a conventional accumulation within an overall basin-centered accumulation (Warner, 1998, 2000).

Figure 17 is an estimated ultimate recovery (EUR) distribution for all producing wells in the Mesaverde–Lance–Fort Union Continuous Gas Assessment Unit, and figure 18 is the EUR distribution divided into thirds based on when the wells were drilled. Median total recovery for producing wells in the assessment unit is 1.6 billion cubic feet of gas (BCFG) (fig. 17), and median total recoveries by thirds are 2.8 BCFG for the earliest third, 1.7 BCFG for the middle third, and 1.3 BCFG for the latest third of wells completed (fig. 18). Thus recoveries per well have significantly declined through time. The vast majority of the producing wells in the assessment unit are in Jonah field and were drilled in the last 10 years, and the decline in productivity with each third is largely a reflection of a progressive decline in productivity for new wells drilled at Jonah field. This decline is possibly due to the best locations being drilled first. In addition, the most recent third includes a significant number of new producers from the rapidly developing Pinedale anticline, and these wells may not be as productive as the wells at Jonah.

Minimum, median, and maximum area per cell of untested cells having potential for additions to reserves in the next 30 years are 40, 100, and 200 acres (Appendix A). There are 454 tested cells in the assessment unit, thus assuming the median well spacing of 100 acres, then 45,400 acres have been tested. The assessment unit therefore is largely untested with minimum, median, and maximum of 97.1, 98.6, and 99.5 percent of the total assessment unit area that is untested. Minimum, median, and maximum percentages of untested assessment-unit area that has potential for additions to reserves in the next 30 years are 14, 24, and 45 percent (Appendix A). The minimum of 14 percent assumes a continued development of the two existing fields, Pinedale and Jonah, but that no other “sweet spots” will be found. The median of 24 percent assumes that several new “sweet spots” similar to Pinedale and Jonah will be discovered and developed. The maximum of 45 percent assumes that a significant amount of the low-grade gas resources found throughout the assessment unit will be developed through improvements in completion and production technologies.

Minimum, median and maximum total recoveries per cell having potential for additions to reserves in the next 30 years are 0.02, 1.2, and 15 BCF (Appendix A). This distribu-

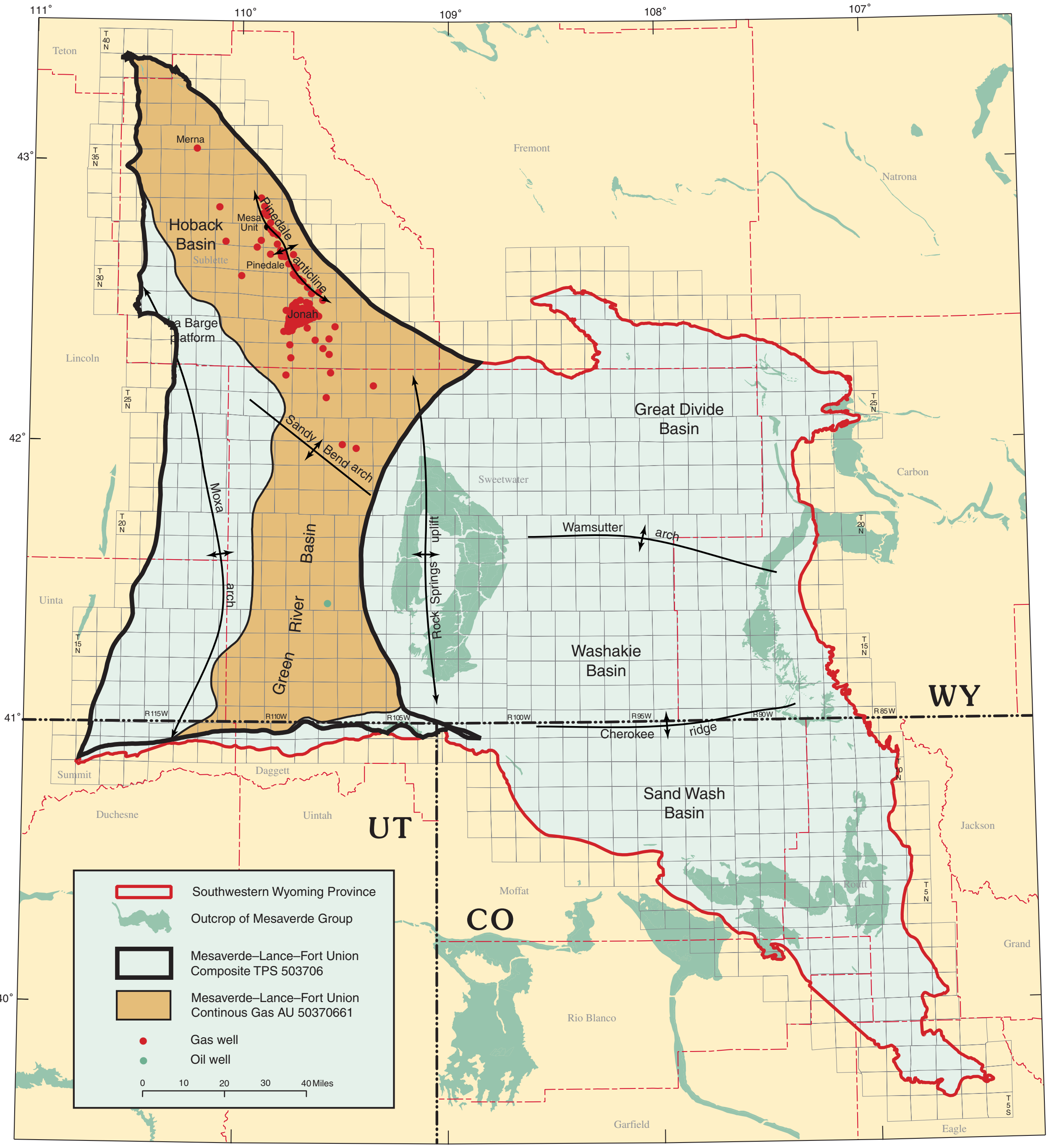

Figure 13. Mesaverde–Lance–Fort Union Continuous Gas Assessment Unit (AU 50370661) in the Mesaverde–Lance–Fort Union Composite Total Petroleum System. The assessment unit is defined as that area where thermal maturities exceed a vitrinite reflectance of 0.8 percent at the base of the total petroleum system.

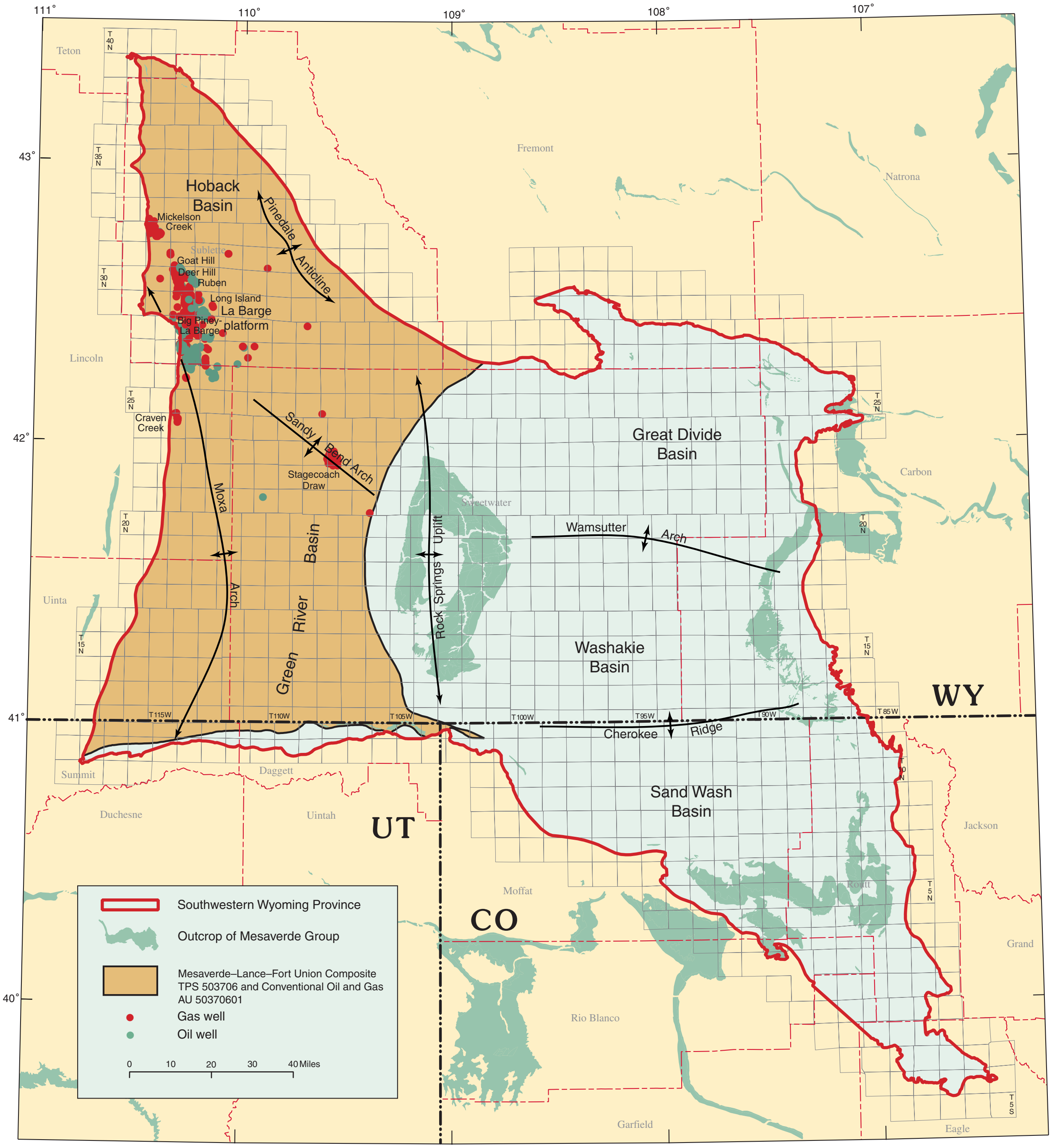

Figure 14. Mesaverde–Lance–Fort Union Conventional Gas Assessment Unit (AU 50370601) in the Mesaverde–Lance–Fort Union Composite Total Petroleum System. The assessment unit covers the entire TPS and overlies the Continuous Gas Assessment Unit.

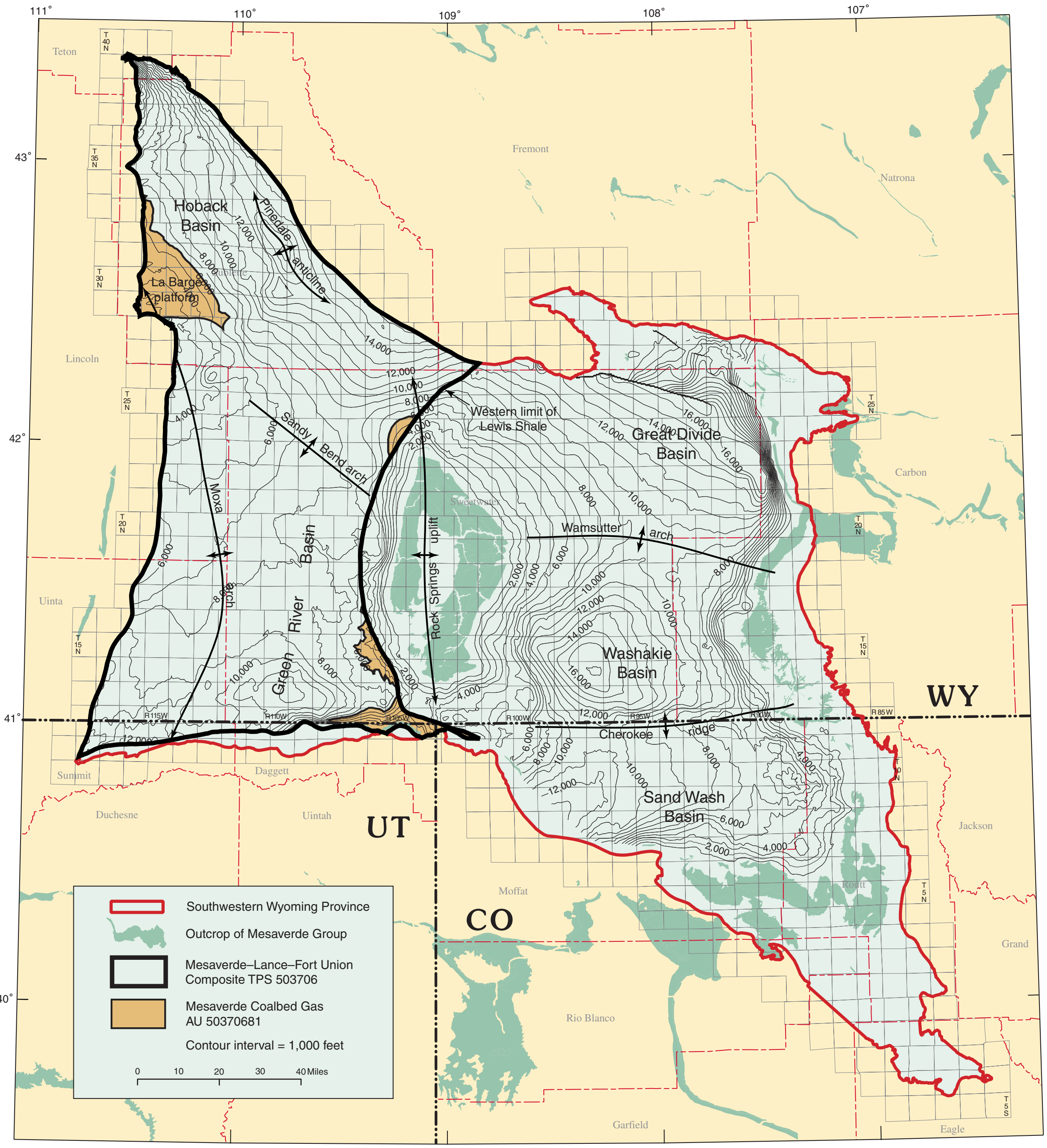

Figure 15. Mesaverde Coalbed Gas Assessment Unit (AU 50370681) in the Mesaverde–Lance–Fort Union Composite Total Petroleum System.

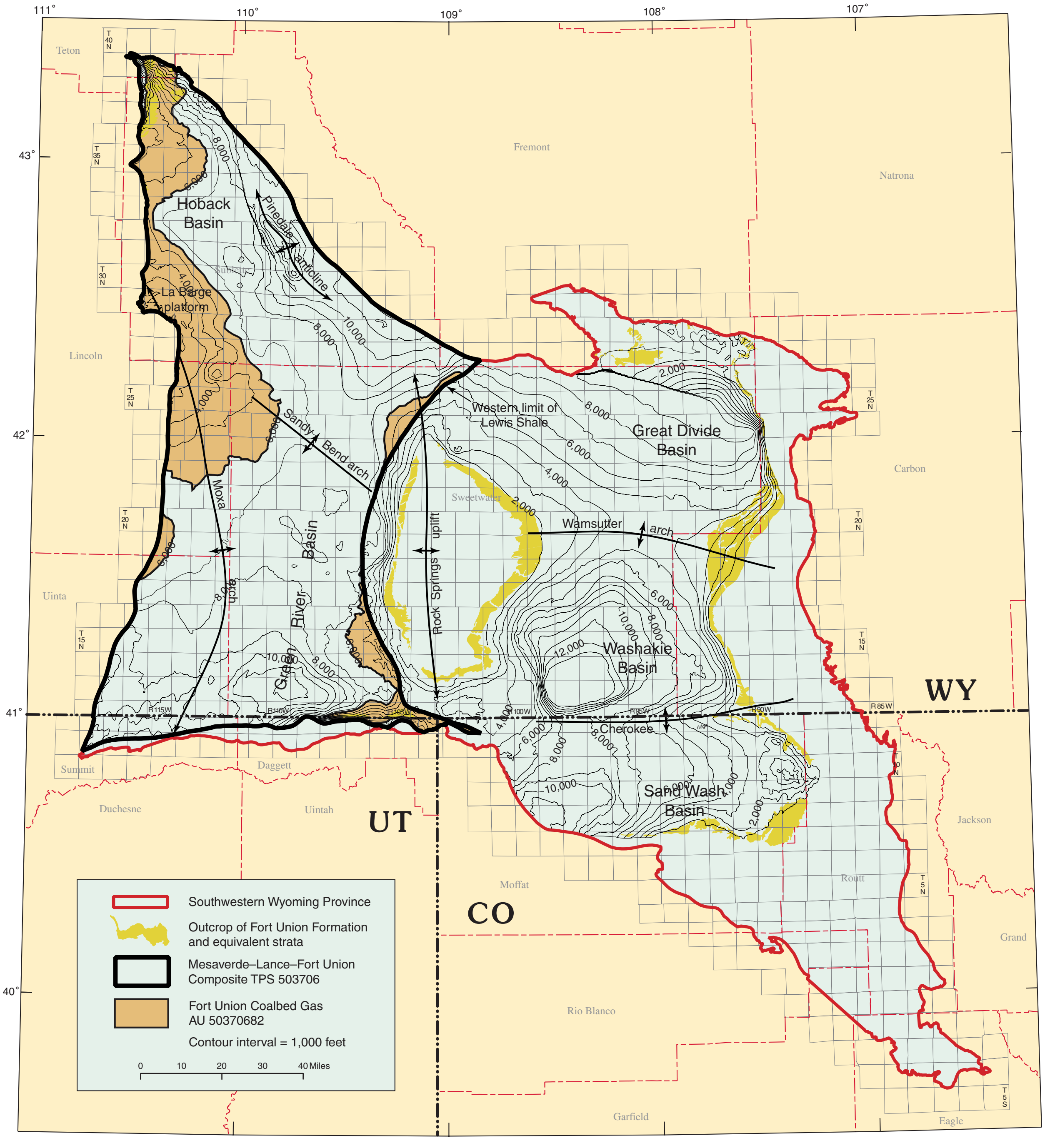

Figure 16. Fort Union Coalbed Gas Assessment Unit (AU 50370682) in the Mesaverde–Lance–Fort Union Composite Total Petroleum System.

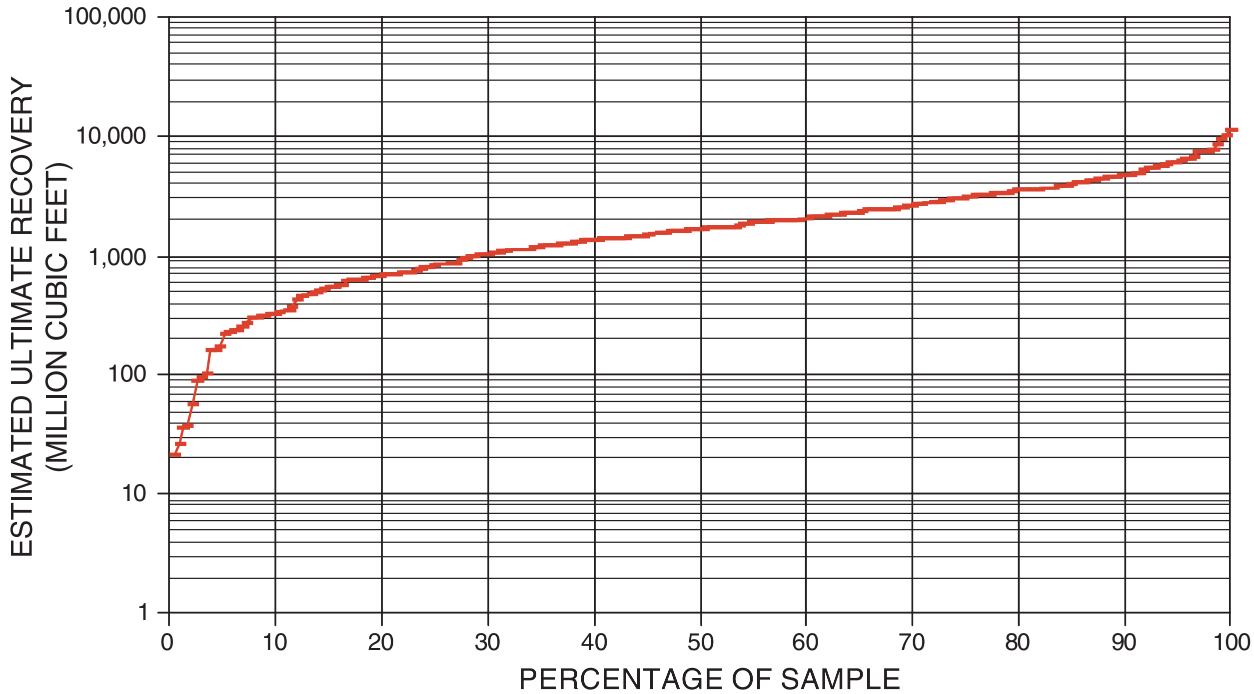

Figure 17. Distribution of estimated ultimate recoveries (EURs) for gas wells within the Mesaverde–Lance–Fort Union Continuous Gas Assessment Unit (AU 50370661) in the Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown.

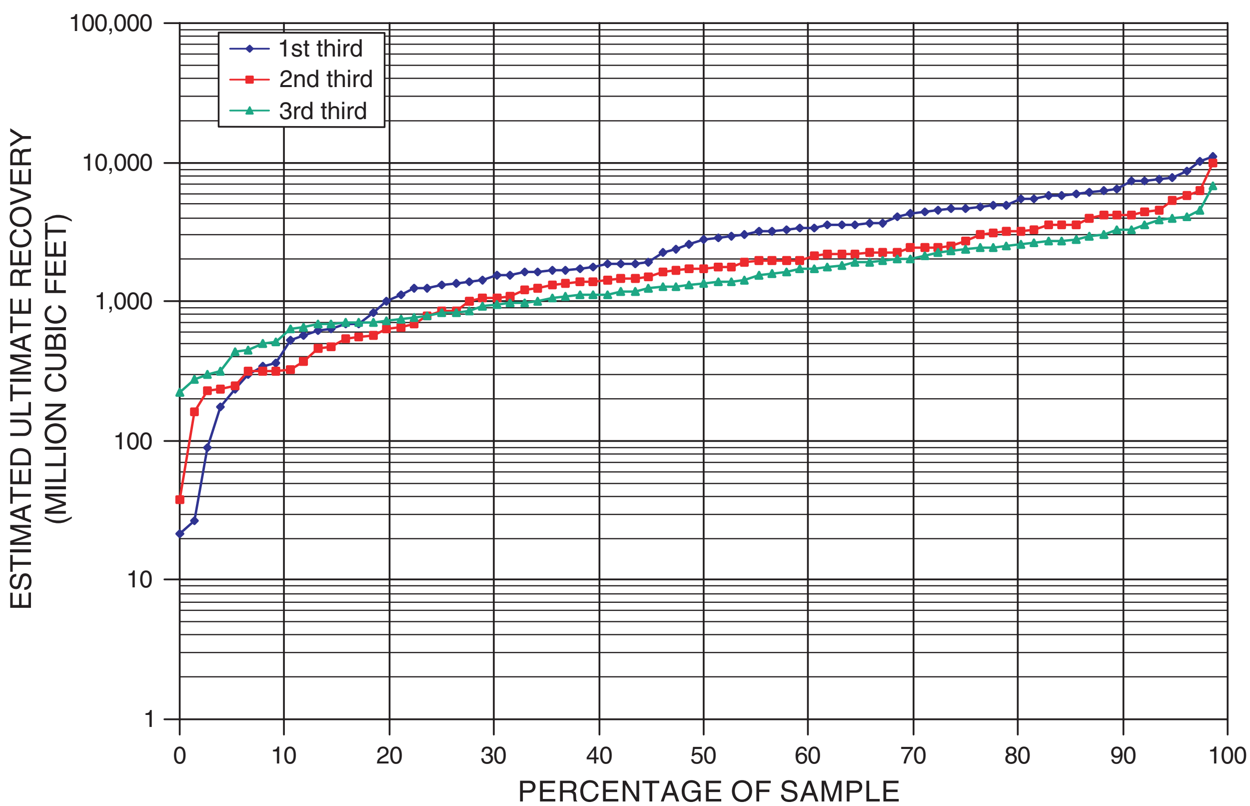

Figure 18. Distribution of estimated ultimate recoveries (EURs) by thirds for gas wells within the Mesaverde–Lance–Fort Union Continuous Gas Assessment Unit (AU 50370661) in the Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown. "Thirds" refers to the division into three parts, over time, of the wells drilled in a given area. The wells are divided by time according to their completion date.

tion, which is similar to that for current production from Jonah field, assumes that future "sweet spots" will be of lower quality than Jonah, but advances in completion technologies will compensate for the lower quality reservoirs. Mean estimate of gas that has potential for additions to reserves over the next 30 years is 13.64 TCF (table 3).

Mesaverde–Lance–Fort Union Conventional Oil and Gas Assessment Unit (AU 50370601)

The Mesaverde–Lance–Fort Union Conventional Oil and Gas Assessment Unit encompasses the entire Composite TPS and includes three oil fields and four gas fields that exceeded the minimum field size considered of 0.5 million barrels of oil equivalent grown (fig. 14). The most recent oil field to be discovered was Ruben field in 1966, and we considered it unlikely that many new oil fields above the minimum size of 0.5 million barrels of oil equivalent (MMBOE) will be discovered in the next 30 years. We estimated a median of two oil fields will be discovered and that these would be comparatively small fields (median size: 1 MMBOE) (table 3).

We considered the potential for future gas field discoveries, in contrast, to be much better. The most recent gas field discovered, Stagecoach Draw field, was discovered in 1993 and is also by far the largest of the four fields discovered to date. Stagecoach Draw field was discovered using a new exploration concept, searching for "marine influenced sandstones" near the pinch-out of the Lewis Shale (Kovach and others, 2001), and we feel that it is likely that this concept and other new concepts will result in significant new gas discoveries during the next 30 years. We estimate a median of 20 new gas fields with a median size of 10 BCFG will be discovered in the assessment unit over the next 30 years (Appendix B). Mean estimate of gas that has potential for additions to reserves over the next 30 years is 9.8 BCFG (table 3).

Mesaverde Coalbed Gas Assessment Unit (AU 50370681)

The Mesaverde Coalbed Gas Assessment Unit encompasses about 327,000 acres and is defined as those areas of the TPS where significant coal occurs in the Rock Springs Formation at depths of 6,000 ft or less. Commercial production rarely extends to depths of greater than 6,000 ft. The AU is divided into four areas, two along the west and southwest flanks of the Rock Springs uplift, one along the north flank of the Uinta Mountains, and one in the La Barge Platform area (fig. 15). Mesaverde coals are truncated beneath younger units along most of the Moxa arch. This AU is hypothetical as there are no producing wells and no tested cells. There have been some attempts to produce coalbed gas from equivalent coals east of the pinch-out of the Lewis Shale in the Mesaverde Total Petroleum System, and these attempts have met with limited success. In the early 1990s, coalbed methane wells were drilled in several areas along the north flank of the Rock Springs uplift, the east flank of the Washakie Basin, and the south flank of the Sand Wash Basin, but these wells typically produced large amounts of water and little gas (Tyler and others, 1995). Interest in the coalbed methane resources of the area was renewed in the last 5 years, and there are now (2005) several active projects in the TPS. These recent wells are currently undergoing dewatering, and gas flows have not as yet peaked.

To aid in our assessment, the Mesaverde Group Coalbed Methane Assessment Unit (AU 50200282) in the Uinta-Piceance Province of Colorado and Utah is used here as an analog for cell sizes and EURs. Coals in both assessment units were deposited in similar lower coastal-plain depositional settings. Attempts to develop coalbed methane in the analog unit have hindered production of low coal permeabilities, undersaturated coal, and excessive water production near areas of major recharge (Reinecke and others, 1991; Johnson and others, 1996).

Minimum, median, and maximum area per cell of untested cells having potential for additions to reserves in the next 30 years are 40, 120, and 280 acres (Appendix C). These are the same values used for the Mesaverde Group Coalbed Methane Assessment Unit in the Uinta-Piceance Province. Minimum, median, and maximum percentages of untested assessment-unit area that has potential for additions to reserves in the next 30 years are 1, 10, and 20 percent (Appendix C). The minimum of 1 percent assumes that the excess amounts of water that have plagued Mesaverde coals east of the pinch-out of the Lewis Shale in the past will be found to be pervasive throughout nearly all of this assessment unit. The median of 10 percent assumes that a limited number of "sweet spots" with low water production, high permeabilities, and high gas contents will be discovered. Our maximum of 20 percent assumes that advanced technologies will overcome high water production and low permeability problems. The lack of coalbed gas at shallow depths in the assessment unit limits the total area that can be developed for coalbed methane. Mean estimate of gas that has potential for additions to reserves over the next 30 years is 27.3 BCFG (table 3).

Fort Union Coalbed Gas Assessment Unit (AU50370682)

The Fort Union Coalbed Gas Assessment Unit (AU50370682) encompasses nearly 1.2 million acres in four separate areas around the margins of the TPS where significant coal is present in the Fort Union Formation at depths of 6,000 ft or less (fig. 16). The AU is also a hypothetical assessment unit with no production and no tested cells. Analogs used for cell sizes and EURs are the Fort Union Coalbed Gas Assessment Unit in the Southwest Wyoming Province east of the pinch-out of Lewis Shale (see Stephen Roberts, Chapter 11, this CD–ROM) and the coalbed gas wells producing from sub-

Table 3. Summary of undiscovered resources that have the potential for additions to reserves in the Mesaverde Total Petroleum System, Southwest Wyoming Province.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Minimum, for conventional resources this is the minimum field size assessed (MMBO or BCFG); for continuous-type resources this is the minimum cell-estimated ultimate recovery assessed. Prob., probability (including both geologic and accessibility probabilities) of at least one field (or, for continuous-type resources, cell) equal to or greater than the minimum. Results shown are fully risked estimates. For gas fields, all liquids are included under the natural gas liquids category. F95 represents a 95-percent chance of producing at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Total Petroleum Systems (TPS) and Assessment Units (AU)	Field type	Total undiscovered resources											
		Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Mesaverde–Lance–Fort Union Composite TPS													
Mesaverde–Lance–Fort Union Conventional Oil and Gas AU	Oil	0.90	2.10	4.00	2.30	3.80	9.10	18.30	9.80	0.20	0.40	0.90	0.40
	Gas					101.40	296.70	558.80	310.40	4.20	13.00	26.90	14.00
Total conventional resources		**0.90**	**2.10**	**4.00**	**2.30**	**105.20**	**305.80**	**577.10**	**320.20**	**4.40**	**13.40**	**27.80**	**14.40**
Mesaverde–Lance–Fort Union Continuous Gas AU	Gas					8,320.10	13,122.00	20,695.40	13,635.20	329.20	578.60	1,016.90	613.60
Mesaverde Coalbed Gas AU	CBG					13.70	25.40	47.30	27.30	0.00	0.00	0.00	0.00
Fort Union Coalbed Gas AU	CBG					35.30	73.20	151.90	80.80	0.00	0.00	0.00	0.00
Total continuous resources						**8,369.10**	**13,220.60**	**20,894.60**	**13,743.30**	**329.20**	**578.60**	**1,016.90**	**613.60**
Total conventional and continuous resources		**0.90**	**2.10**	**4.00**	**2.30**	**8,474.30**	**13,526.40**	**21,471.70**	**14,063.50**	**333.60**	**592.00**	**1,044.70**	**628.00**

bituminous Anderson and Canyon coalbeds of the Fort Union Formation in the Powder River Basin.

Ranks of Fort Union coals within the TPS are mostly subbituminous to high-volatile C bituminous (Tyler and others, 1995). This compares to Fort Union coals in the Powder River Basin that are mainly subbituminous (Stricker and others, 1998). In general, coalbed thicknesses in the Fort Union Formation in this assessment unit are also comparable to thicknesses reported for the Anderson and Canyon coalbeds. Tyler and others (1995) reported individual coalbed thicknesses of as much as 40 ft within the area now included in the Fort Union Coalbed Gas Assessment Unit. Glass (1980) reports that the Anderson coalbed in the Powder River Basin ranges from 10 to 50 ft thick and the Canyon coalbed ranges from 11 to 65 ft thick.

Tyler and others (1995, their fig. 50) show two areas with thick Fort Union coal accumulations, one running generally north-northeast near the synclinal axis of the Green River Basin and another much smaller area in the northwest corner of the Hoback Basin. The first follows a major northeast-trending trunk stream with the thickest coalbeds occurring above or on the flanks of the thickest fluvial sandstones (Tyler and others, 1995). Both of these areas with thick coal accumulations are largely at depths of greater than 6,000 ft and thus are outside the area included in this assessment unit. Total coal thicknesses within the assessment unit generally average from 10 to 60 ft.

Minimum, median, and maximum area per cell of untested cells having potential for additions to reserves in the next 30 years are 40, 80, and 140 acres (Appendix D). These are the same cell sizes applied to Powder River coalbeds (R.M. Flores, U.S. Geological Survey, oral commun., 2003). Percentage of untested assessment-unit area that has potential for additions to reserves in the next 30 years are 1, 4, and 10 percent (Appendix D). These percentages are comparatively low because much of the areas of thick Fort Union coals in the Mesaverde–Lance–Fort Union Composite TPS are at depths of greater than 6,000 ft and thus not included in the assessment unit and because there has been no production established in these coalbeds to date. Mean estimate of gas that has potential for additions to reserves over the next 30 years is 80.8 BCFG (table 3).

Summary of Results

Tabulated results of undiscovered oil, gas, and gas liquids in the Mesaverde–Lance–Fort Union Composite Total Petroleum System that have the potential for additions to reserves are listed in Appendix C. Mean estimate of the total oil is 2.30 MMBO, total gas is 14.06 TCF, and total gas liquids is 628 MMBNGL. All of the undiscovered oil is in the Mesaverde Conventional Oil and Gas Assessment Unit. For gas, 13.64 TCF is in the Mesaverde–Lance–Fort Union Continuous Gas Assessment Unit, 27.3 BCF is in the Mesaverde Coalbed Gas Assessment Unit, and 80.8 BCF is in the Fort Union Coalbed Gas Assessment Unit, and 9.8 BCF is in the Conventional Oil and Gas Assessment Unit.

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Appendix A. Input parameters and calculations of potential additions to reserves for the Continuous Gas Assessment Unit (AU 50370661), Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 7, 6-30-00)

IDENTIFICATION INFORMATION

Assessment Geologist:…	R.C. Johnson, T.M. Finn, and S.B. Roberts	Date:	8/22/2002
Region:……………………	North America	Number:	5
Province:………………….	Southwestern Wyoming	Number:	5037
Total Petroleum System:.	Mesaverde-Lance-Fort Union Composite	Number:	503706
Assessment Unit:……….	Mesaverde-Lance-Fort Union Continuous Gas	Number:	50370661
Based on Data as of:……	IHS Energy Group, 2001, Wyoming Oil and Gas Conservation Commission		
Notes from Assessor…..			

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: **Oil** (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo) Gas
What is the minimum total recovery per cell?… 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 454
Number of tested cells with total recovery per cell ≥ minimum: ……... 248
Established (>24 cells ≥ min.) X Frontier (1-24 cells) ____ Hypothetical (no cells) ____
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st third discovered 2.8 2nd third 1.7 3rd third 1.3

Assessment-Unit Probabilities:

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

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

4. **ACCESS:** Adequate location for necessary petroleum-related activities for an untested cell with total recovery ≥ minimum ……………………………………………………………… 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES IN THE NEXT 30 YEARS

1. Total assessment-unit area (acres): (uncertainty of a fixed value)
minimum 3,134,000 median 3,482,000 maximum 3,830,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres):
(values are inherently variable)
calculated mean 105 minimum 40 median 100 maximum 200

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 97.1 median 98.6 maximum 99.5

4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum)
(uncertainty of a fixed value) minimum 14 median 24 maximum 45

Appendix A. Input parameters and calculations of potential additions to reserves for the Continuous Gas Assessment Unit (AU 50370661), Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province.—Continued

Assessment Unit (name, no.)
Mesaverde-Lance-Fort Union Continuous Gas, Assessment Unit 50370661

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves in next 30 years:
(values are inherently variable)

	minimum	median	maximum
(mmbo for oil A.U.; bcfg for gas A.U.)	0.02	1.2	15

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

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)………………………..…….			
NGL/gas ratio (bngl/mmcfg)…………………….….			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)….……………..……	22.5	45	67.5

SELECTED ANCILLARY DATA FOR UNTESTED CELLS
(values are inherently variable)

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)…………….………….			
Sulfur content of oil (%)………………………...….			
Drilling depth (m) ……………...…………….……			
Depth (m) of water (if applicable)……………….			
Gas assessment unit:			
Inert-gas content (%)……………………….....…..	0.00	1.70	6.10
CO_2 content (%)……………………………….…...	0.10	0.80	5.70
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)………………………………….	2,440	3,050	5,200
Depth (m) of water (if applicable)……………….			

Success ratios:	calculated mean	minimum	median	maximum
Future success ratio (%)..	80	70	80	90

Historic success ratio, tested cells (%) 60

Appendix B. Input parameters and calculations of potential additions to reserves for the Conventional Gas Assessment Unit (AU 50370601), Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province.

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (NOGA, Version 5, 6-30-01)

IDENTIFICATION INFORMATION

Assessment Geologist	R.C. Johnson and T.M. Finn	Date:	8/22/2002
Region:………………	North America	Number:	5
Province:…………….	Southwestern Wyoming	Number:	5037
Total Petroleum Syste	Mesaverde-Lance-Fort Union Composite	Number:	503706
Assessment Unit:……	Mesaverde-Lance-Fort Union Conventional Oil and Gas	Number:	50370601
Based on Data as of:..	NRG 2001 (data current through 1999), IHS Energy Group, 2001		
Notes from Assessor..	NRG Reservoir Lower 48 growth function		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall):.. Oil

What is the minimum accumulation size?………. 0.5 mmboe grown
(the smallest accumulation that has potential to be added to reserves in the next 30 years)

No. of discovered accumulations exceeding minimum size:…… Oil: 3 Gas: 4
Established (>13 accums.) ____ Frontier (1-13 accums.) X Hypothetical (no accums.) ____

Median size (grown) of discovered oil accumulation (mmbo):
1st third ____ 2nd third ____ 3rd third ____
Median size (grown) of discovered gas accumulations (bcfg):
1st third 11 2nd third 41 3rd third ____

Assessment-Unit Probabilities:

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

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

4. **ACCESSIBILITY:** Adequate location to allow exploration for an undiscovered accumulation ≥ minimum size………………………………………………..………………..……..………… 1.0

UNDISCOVERED ACCUMULATIONS

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

	min. no. (>0)	median no.	max no.
Oil Accumulations:…………………	1	2	3
Gas Accumulations:………………	2	20	40

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

	min. size	median size	max. size
Oil in Oil Accumulations (mmbo):…..….	0.5	1	5
Gas in Gas Accumulations (bcfg):….….	3	10	200

Appendix B. Input parameters and calculations of potential additions to reserves for the Conventional Gas Assessment Unit (AU 50370601), Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province.—Continued

(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum	median	maximum
Gas/oil ratio (cfg/bo)	2,156	4,312	6,468
NGL/gas ratio (bngl/mmcfg)	22	44	66

Gas Accumulations:	minimum	median	maximum
Liquids/gas ratio (bliq/mmcfg)	22.5	45	67.5
Oil/gas ratio (bo/mmcfg)			

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS

(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	median	maximum
API gravity (degrees)	40	41.5	43.1
Sulfur content of oil (%)	0	0.01	0.02
Drilling Depth (m)	300	1,400	1,800
Depth (m) of water (if applicable)			

Gas Accumulations:	minimum	median	maximum
Inert gas content (%)	0.1	1.5	20
CO_2 content (%)	0.1	0.5	1.8
Hydrogen-sulfide content (%)	0	0	0
Drilling Depth (m)	600	1,800	2,700
Depth (m) of water (if applicable)			

Appendix C. Input parameters and calculations of potential additions to reserves for the Mesaverde Coalbed Gas Assessment Unit (AU 50370681), Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 7, 6-30-00)

IDENTIFICATION INFORMATION

Assessment Geologist:…	R.C. Johnson and T.M. Finn	Date:	8/22/2002
Region:……………………	North America	Number:	5
Province:………………….	Southwestern Wyoming	Number:	5037
Total Petroleum System:.	Mesaverde-Lance-Fort Union Composite	Number:	503706
Assessment Unit:……….	Mesaverde Coalbed Gas	Number:	50370681
Based on Data as of:……			
Notes from Assessor…..	Analog: Mesaverde Coalbed Gas of the eastern portion of SW Wyoming Province		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo) Gas
What is the minimum total recovery per cell?… 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 0
Number of tested cells with total recovery per cell ≥ minimum: ……... 0
Established (>24 cells ≥ min.) ______ Frontier (1-24 cells) ______ Hypothetical (no cells) X
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st third discovered ______ 2nd third ______ 3rd third ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum ……	1.00
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	1.00
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum………..	1.00

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

4. **ACCESS:** Adequate location for necessary petroleum-related activities for an untested cell with total recovery ≥ minimum ……………………………………………………………… 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES IN THE NEXT 30 YEARS

1. Total assessment-unit area (acres): (uncertainty of a fixed value)
minimum 311,000 median 327,000 maximum 343,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres): (values are inherently variable)
calculated mean 129 minimum 40 median 120 maximum 280

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 100 median 100 maximum 100

4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum)
(uncertainty of a fixed value) minimum 1 median 10 maximum 20

Appendix C. Input parameters and calculations of potential additions to reserves for the Mesaverde Coalbed Gas Assessment Unit (AU 50370681) Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province.—Continued

Assessment Unit (name, no.)
Mesaverde Coalbed Gas, Assessment Unit 50370681

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves in next 30 years:
(values are inherently variable)

	minimum	median	maximum
(mmbo for oil A.U.; bcfg for gas A.U.)	0.02	0.06	2

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS

(uncertainty of fixed but unknown values)

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)……………………...…….			
NGL/gas ratio (bngl/mmcfg)…………………..….			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)………………..……	0	0	0

SELECTED ANCILLARY DATA FOR UNTESTED CELLS

(values are inherently variable)

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)………………..………			
Sulfur content of oil (%)…………………….....….			
Drilling depth (m) ……………...………………..……			
Depth (m) of water (if applicable)……………….			
Gas assessment unit:			
Inert-gas content (%)……………………......…..	1.00	4.00	20.00
CO_2 content (%)………………………………..…..	1.00	6.70	27.00
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)……………………………………	150	1,200	1,800
Depth (m) of water (if applicable)……………….			

Success ratios:	calculated mean	minimum	median	maximum
Future success ratio (%)..	48	10	50	65

Historic success ratio, tested cells (%) ______

Appendix D. Input parameters and calculations of potential additions to reserves for the Fort Union Coalbed Gas Assessment Unit (AU 50370682) Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province.

FORSPAN ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 7, 6-30-00)

IDENTIFICATION INFORMATION

Assessment Geologist:…	R.C. Johnson and T.M. Finn	Date:	8/22/2002
Region:……………………	North America	Number:	5
Province:………………….	Southwestern Wyoming	Number:	5037
Total Petroleum System:.	Mesaverde-Lance-Fort Union Composite	Number:	503706
Assessment Unit:……….	Fort Union Coalbed Gas	Number:	50370682
Based on Data as of:……			
Notes from Assessor…..	Analogs: Fort Union Coalbed Gas of eastern SW Wyoming Province		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: **Oil** (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo) Gas
What is the minimum total recovery per cell?… 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 0
Number of tested cells with total recovery per cell ≥ minimum: ……... 0
Established (>24 cells ≥ min.) ____ Frontier (1-24 cells) ____ Hypothetical (no cells) X
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st third discovered ____ 2nd third ____ 3rd third ____

Assessment-Unit Probabilities:

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

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

4. **ACCESS:** Adequate location for necessary petroleum-related activities for an untested cell with total recovery ≥ minimum ……………………………………………………………… 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES IN THE NEXT 30 YEARS

1. Total assessment-unit area (acres): (uncertainty of a fixed value)
minimum 1,126,000 median 1,185,000 maximum 1,244,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres):
(values are inherently variable)
calculated mean 83 minimum 40 median 80 maximum 140

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 100 median 100 maximum 100

4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum)
(uncertainty of a fixed value) minimum 1 median 4 maximum 10

Appendix D. Input parameters and calculations of potential additions to reserves for the Fort Union Coalbed Gas Assessment Unit (AU 50370682) Mesaverde–Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province.—Continued

(mmbo for oil A.U.; bcfg for gas A.U.) minimum 0.02 median 0.1 maximum 1

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

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)………………………...…….			
NGL/gas ratio (bngl/mmcfg)……………………..….			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)…………………..…..	0	0	0

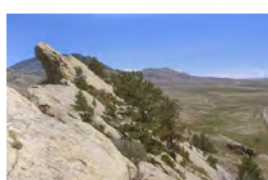
SELECTED ANCILLARY DATA FOR UNTESTED CELLS
(values are inherently variable)

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)…………………..……….			
Sulfur content of oil (%)………………………...…..			
Drilling depth (m) ……………...…………….…..….			
Depth (m) of water (if applicable)……………….			

Gas assessment unit:	minimum	median	maximum
Inert-gas content (%)……………………….....…..	1.00	4.00	20.00
CO_2 content (%)……………………………….....…..	4.20	5.40	6.90
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)………………………………….	1,200	1,500	1,830
Depth (m) of water (if applicable)……………….			

Success ratios:	calculated mean	minimum	median	maximum
Future success ratio (%)..	71	50	70	95

Historic success ratio, tested cells (%) ______



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