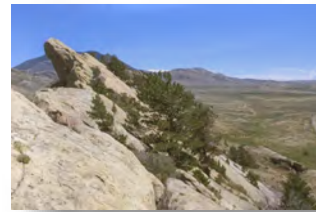
Chapter 8

# The Mesaverde Total Petroleum System, Southwestern Wyoming Province



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**Volume Title Page**

By Ronald C. Johnson, Thomas M. Finn, and Laura N.R. Roberts

Chapter 8 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 Total Petroleum System, Southwestern Wyoming Province

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## Abstract

The Mesaverde Total Petroleum System in the Southwestern Wyoming Province includes most but not all strata in the Mesaverde Group east of the pinch-out of the Lewis Shale. The Total Petroleum System was subdivided into three continuous gas assessment units—the Almond Continuous Gas Assessment Unit, the Rock Springs–Ericson Continuous Gas Assessment Unit, and the Mesaverde Coalbed Gas Assessment Unit—and one conventional assessment unit, the Mesaverde Conventional Oil and Gas Assessment Unit. Variations in thermal maturity as measured by variations in vitrinite reflectance were used to define the four assessment units.

Estimates of undiscovered resources that have the potential for additions to reserves were made for the four assessment units. The mean estimate of the total oil is 2.30 million barrels of oil, mean total gas is 25.83 trillion cubic feet, and the mean estimate of total gas liquids is 347.40 million barrels of natural gas liquids. For gas, 13.35 trillion cubic feet is in the Almond Continuous Gas Assessment Unit, 12.18 trillion cubic feet is in the Rock Springs–Ericson Continuous Gas Assessment Unit, and 248.70 billion cubic feet is in the Mesaverde Coalbed Gas Assessment Unit. All of the undiscovered oil is in the Mesaverde Conventional Oil and Gas Assessment Unit.


## Introduction

The Mesaverde Total Petroleum System (TPS) in the Southwestern Wyoming Province produces hydrocarbons from sandstone and coal reservoirs in the Upper Cretaceous Mesaverde Group. Coals and organic-rich shales within the Mesaverde Group are believed to be the primary source. The Mesaverde TPS encompasses about 11,500 $mi^2$ of the eastern part of the Southwestern Wyoming Province where the Lewis Shale is present. The Lewis Shale, which overlies the Mesaverde Group and pinches out along the west flank of the Rock Springs uplift (fig. 1), forms a regional seal separating the Mesaverde Total Petroleum System from the overlying Lewis Total Petroleum System. West of the pinch-out, there is no regional seal separating the Mesaverde Total Petroleum System from overlying continental rocks of Late Cretaceous and Paleocene age, and the Mesaverde Group is combined with the overlying Upper Cretaceous Lance and Paleocene Fort Union Formations to form the Mesaverde–Lance–Fort Union Composite Total Petroleum System. The northern, eastern, and southern boundaries of the Mesaverde TPS are approximately defined by the limits of Mesaverde Group within the Southwestern Wyoming Province.

The Mesaverde TPS includes most but not all strata in the Mesaverde Group east of the pinch-out of the Lewis Shale. Because the source of hydrocarbons in the Mesaverde TPS is considered to be mainly coal and organic-rich shale within the Mesaverde Group, units that are stratigraphically below the lowest coaly interval, including the Blair and Haystack Mountains Formations of the Mesaverde Group, are assigned to the underlying Hilliard-Baxter-Mancos TPS. We believe that hydrocarbons in these units are sourced by organic-rich intervals in the Hilliard, Baxter, and Mancos Shales. Some gas derived from these marine shale source rocks probably also migrated vertically into the overlying Mesaverde TPS, but the amount is thought to be comparatively small. In the Rock Springs uplift area the Mesaverde TPS includes the Rock Springs Formation, the Ericson Sandstone, and the Almond Formation; in the eastern part of the Great Divide and Washakie Basins it includes the Allen Ridge Formation, Pine Ridge Sandstone, and Almond Formation; and in the Sand Wash Basin, the TPS includes the Iles and Williams Fork Formations (figs. 2–4). The upper limit of the Mesaverde TPS is placed at the top of the highest marginal marine bar sandstone in the Almond Formation. These bar sandstones are largely sealed from source rocks in the overlying Lewis Shale by the thick marine shales in the lower part of the Lewis Shale.

The Mesaverde Total Petroleum System is divided into four assessment units: three unconventional continuous-type assessment units—the Almond Continuous Gas Assessment Unit (50370561), the Rock Springs–Ericson Continuous Gas Assessment Unit (50370562), and the Mesaverde Coalbed Gas Assessment Unit (50370581)—and one conventional assessment unit, the Mesaverde Conventional Oil and Gas Assessment Unit (50370501). The majority of hydrocarbons produced from the Mesaverde TPS to date have been from marginal marine bar sandstones in the upper part of the Almond Formation. Most of the oil produced from the Mesaverde TPS is from these bar sandstones in the Mesaverde

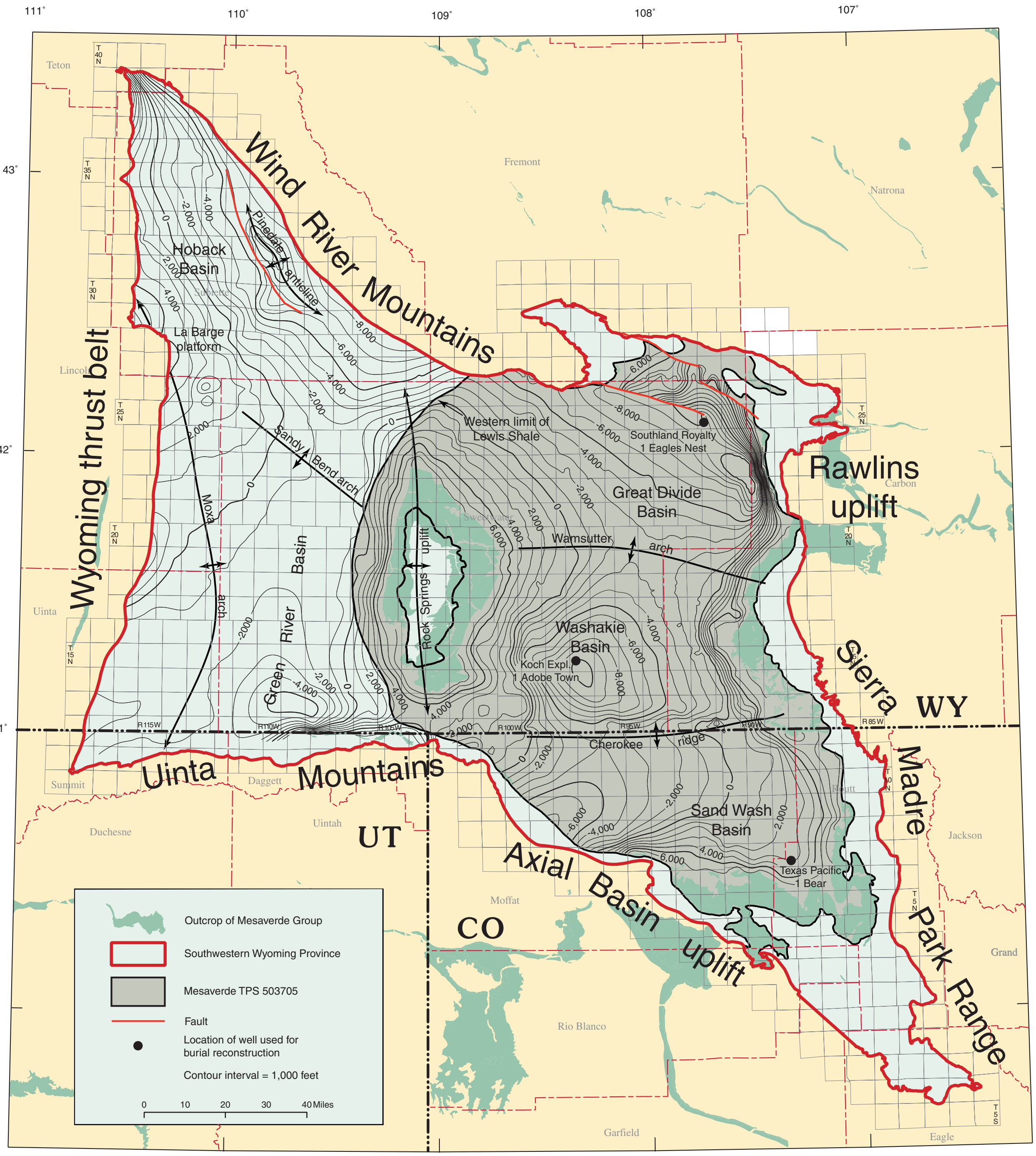


**Figure 1.** Index map showing distribution of Mesaverde Group outcrops, areal extent of the Mesaverde Total Petroleum System, and structural elements in the Southwestern Wyoming Province. Structure contours drawn on top of Mesaverde Group. Contour interval is 1,000 feet. Locations of wells used to construct burial histories also shown.

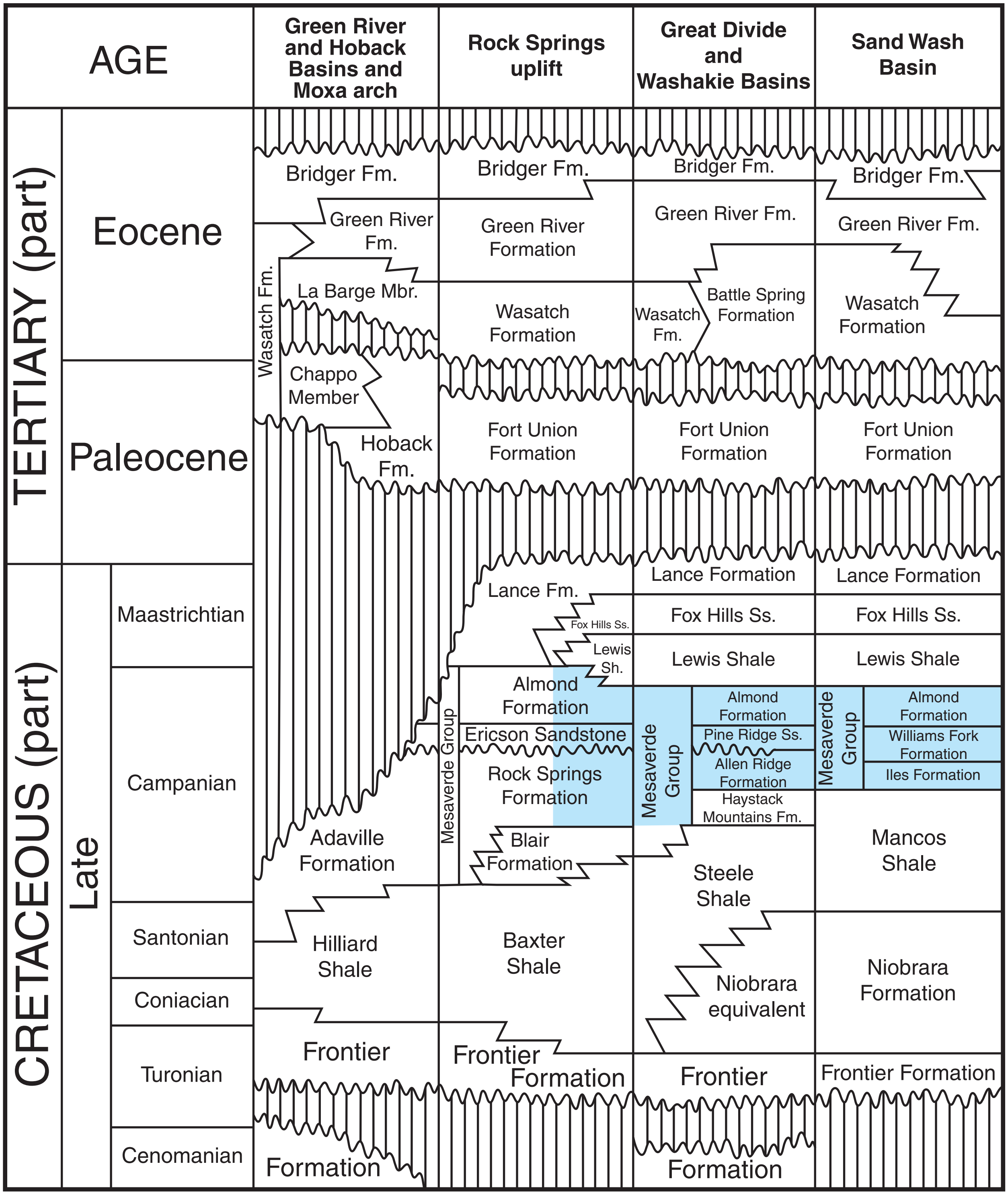


**Figure 2.** Generalized correlation chart for Upper Cretaceous and lower Tertiary stratigraphic units in the Southwestern Wyoming Province. Mesaverde Total Petroleum System shown in blue. Modified from Ryder (1988).

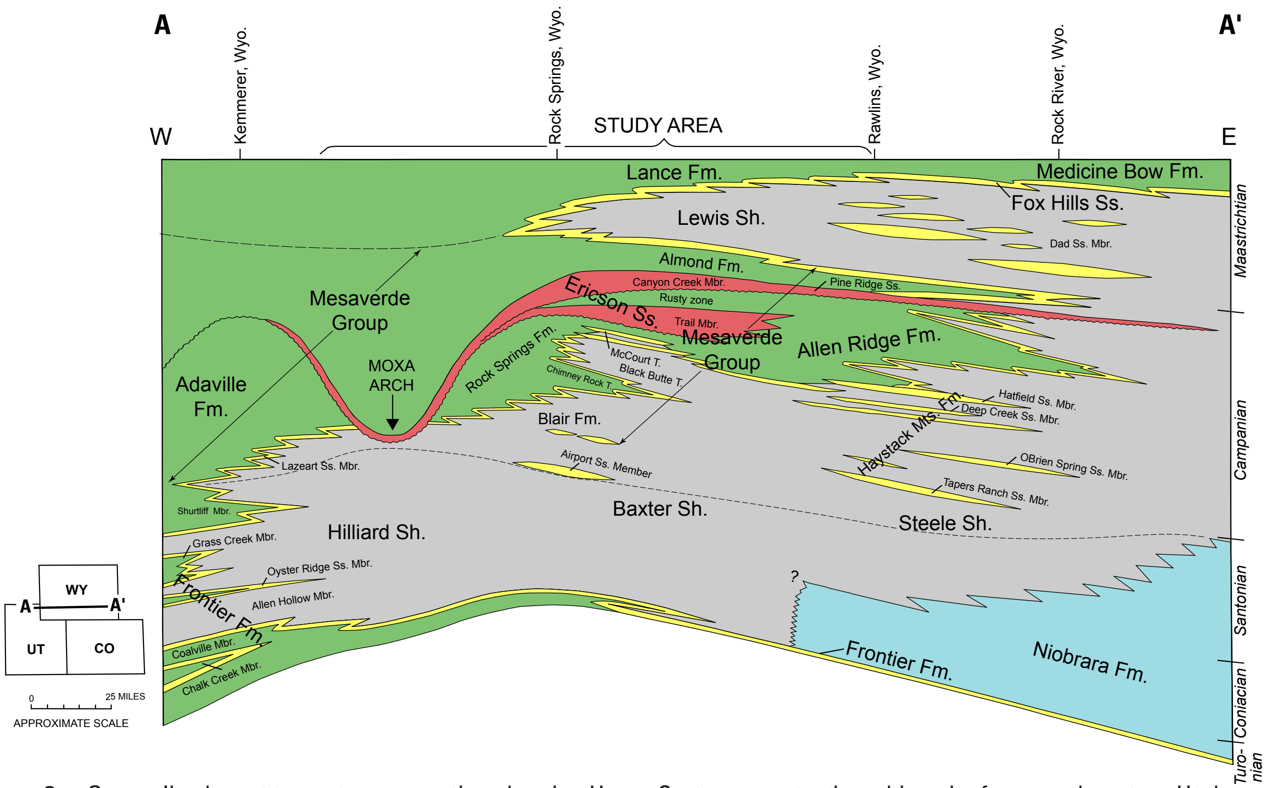


**Figure 3.** Generalized west to east cross section showing Upper Cretaceous stratigraphic units from northeastern Utah to southeastern Wyoming. Approximate limits of Southwestern Wyoming Province shown in brackets. Modified from Roehler (1990, his fig. 7). Abbreviations used: Fm., Formation; Mbr.,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

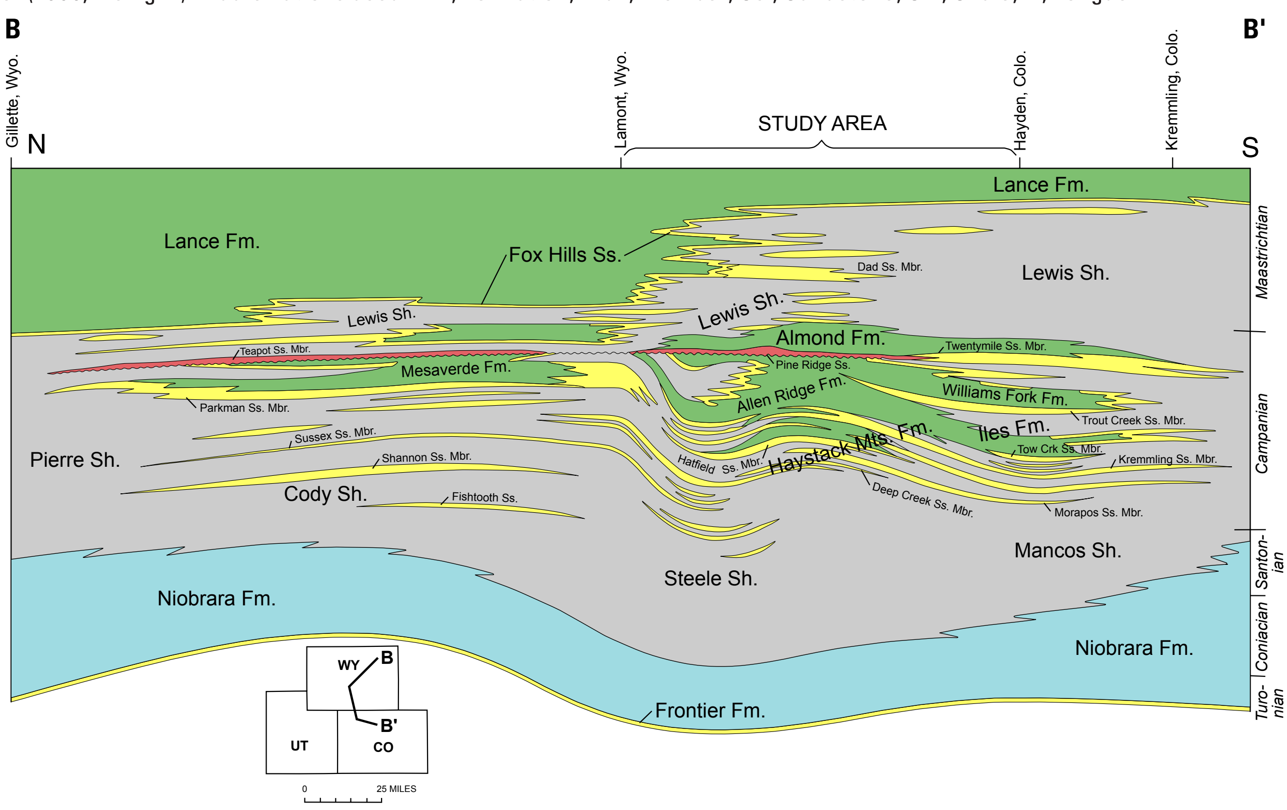


**Figure 4.** Generalized north-south cross section showing Upper Cretaceous stratigraphic units from northeastern Wyoming to north-central Colorado. Approximate limits of Southwestern Wyoming Province shown in brackets. Modified from Roehler (1990, his fig. 9). Abbreviations used: Fm., Formation, Mbr., Member; Ss., Sandstone; Sh., Shale.

Conventional Oil and Gas Assessment Unit (50370501) along the east flank of the Rock Springs uplift, whereas these bar sandstones have produced most of the gas from the Almond Continuous Gas Assessment Unit (50370561) along the Wamsutter arch between the Washakie and Great Divide Basins (fig. 1). Only minor amounts of hydrocarbons have been produced thus far from formations in the Mesaverde Group below the Almond, although much of the mean estimate of 3,347 trillion cubic feet (TCF) of in-place gas estimated by Law and others (1989) in the Mesaverde Group is in these formations.

Tabulated results of undiscovered oil, gas, and gas liquids in the Mesaverde TPS that have the potential for additions to reserves are listed in table 1. The mean estimate of the total oil is 2.30 million barrels of oil (MMBO), mean total gas is 25.83 TCF, and the mean estimate of total gas liquids is 347.40 million barrels of natural gas liquids (MMBNGL). For gas, 13.35 TCF is in the Almond Continuous Gas Assessment Unit, 12.18 TCF is in the Rock Springs–Ericson Continuous Gas Assessment Unit, and 248.70 billion cubic feet (BCF) is in the Mesaverde Coalbed Gas Assessment Unit. All of the undiscovered oil is in the Mesaverde Conventional Oil and Gas Assessment Unit.

## Acknowledgments

The authors wish to thank Richard M. Pollastro and Christopher J. Schenk of the U.S. Geological Survey (USGS) National Oil and Gas Assessment team for discussions regarding the assessment of the Mesaverde Total Petroleum System. We would also like to thank Troy Cook (USGS) for interpretations of production data and for providing graphs of EURs; Philip H. Nelson and Joyce Kibler (USGS) for providing drill-stem test and pressure data; Laura Roberts (USGS) for providing key maps and burial history and petroleum-generation models; and Paul G. Lillis and Michael Lewan (USGS) for providing geochemical data and numerous discussions regarding organic geochemistry and source rocks. The manuscript was reviewed by Stephen B. Roberts and Christopher J. Schenk (USGS) who provided many helpful comments and suggestions.

Table 1. Summary of undiscovered oil and gas resources that have the potential for additions to reserves in the Mesaverde Total Petroleum System, Southwestern Wyoming Province.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 denotes a 95-percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. CBG denotes coalbed gas. 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 TPS** | | | | | | | | | | | | | |
| Mesaverde Conventional Oil and Gas AU | ***Oil*** | 0.90 | 2.10 | 4.00 | 2.30 | 7.40 | 17.30 | 34.80 | 18.80 | 0.30 | 0.60 | 1.40 | 0.70 |
| | ***Gas*** | | | | | 13.40 | 34.00 | 69.40 | 36.90 | 0.10 | 0.40 | 0.90 | 0.40 |
| **Total conventional resources** | | **0.90** | **2.10** | **4.00** | **2.30** | **20.80** | **51.30** | **104.20** | **55.70** | **0.40** | **1.00** | **2.30** | **1.10** |
| | | | | | | | | | | | | | |
| Almond Continuous Gas AU | | | | | | | | | | | | | |
| | ***Gas*** | | | | | 10,013.50 | 13,166.10 | 17,311.30 | 13,349.70 | 113.50 | 190.60 | 319.90 | 200.20 |
| Rock Springs–Ericson Continuous Gas AU | | | | | | | | | | | | | |
| | ***Gas*** | | | | | 8,768.90 | 11,962.80 | 16,320.00 | 12,178.00 | 89.20 | 140.70 | 221.70 | 146.10 |
| Mesaverde Coalbed Gas AU | | | | | | | | | | | | | |
| | ***Gas*** | | | | | 126.10 | 232.10 | 427.30 | 248.70 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total continuous resources** | | | | | | **18,908.50** | **25,361.00** | **34,058.60** | **25,776.40** | **202.70** | **331.30** | **541.60** | **346.30** |
| | | | | | | | | | | | | | |
| **Total conventional and continuous resources** | | **0.90** | **2.10** | **4.00** | **2.30** | **18,929.30** | **25,412.30** | **34,162.80** | **25,832.10** | **203.10** | **332.30** | **543.90** | **347.40** |

# Hydrocarbon Source Rock

Hydrocarbons in the Mesaverde TPS are thought to be largely sourced by coals and organic-rich shales within the Mesaverde Group. However, because the Mesaverde TPS extensively interfingers with the underlying Hilliard-Baxter-Mancos TPS and is probably not effectively sealed off from that petroleum system, it is likely that some of the gas in the Mesaverde TPS was sourced by marine shales in the Hilliard-Baxter-Mancos TPS. Mesaverde source rocks contain mainly Type-III organic matter, which primarily generates gas during maturation, but some Type-II organic matter, which generates both gas and oil, is also present because of the large oil fields producing from the Mesaverde TPS. Coal and associated organic-rich shales are present in all stratigraphic units in the Mesaverde TPS; total coal thicknesses of more than 100 ft are present in the Rock Springs Formation northeast of the Rock Springs uplift (Tyler and others, 1995, fig. 29) and in the Williams Fork Formation in the Sand Wash Basin (Tyler and others, 1995, fig. 33). Coal beds in the Almond Formation have a significant potential to generate oil as well as gas (MacGowan and others, 1992; Garcia-Gonzalez and Surdam, 1992), and these coals may be the source of much of the oil produced from the Almond Formation at the prolific Patrick Draw field (Garcia-Gonzalez and Surdam, 1992).

# Source Rock Maturation

Figures 5 and 6 are maps showing thermal maturities as measured by vitrinite reflectance ($R_o$) at the base and top, respectively, of the Mesaverde TPS. Maximum thermal maturities at the base of the Mesaverde TPS are greater than 2.2 percent $R_o$ in the deepest part of the Washakie Basin and greater than 2.0 percent $R_o$ in the deepest part of the Great Divide Basin (fig. 5). Maximum maturities at the top of the Mesaverde TPS are greater than 2.2 percent $R_o$ in the deepest part of the Washakie Basin and greater than 1.6 percent $R_o$ in the deepest part of the Great Divide Basin (fig. 6). Thermal maturities at both the top and base of the Mesaverde are about 0.6 percent $R_o$ along the margins of the TPS.

Burial reconstructions were made for three wells within the TPS: the Southland Royalty No. 1 Eagles Nest well (sec. 29, T. 25 N., R. 91 W.) near the deep trough of the Great Divide Basin, the Koch No. 1 Adobe Town well (sec. 20, T. 15 N., R. 97 W.) in the deepest part of the Washakie Basin, and the Texas Pacific No. 1 Bear well (sec. 26, T. 7 N., R. 89 W.) on the east flank of the Sand Wash Basin and considerably east of the deep basin trough (fig. 1).

Roberts and others (Chapter 3, 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. Changes in vitrinite reflectance ($R_o$) are used as an index for changes in organic-matter maturation. A mass-balance approach, which calculates the amount of hydrocarbons generated based on changes in hydrogen: carbon (H/C) and oxygen:carbon (O/C) ratios in kerogen as it undergoes maturation, is commonly used. Juntgen and Karweil (1966) were the first to use the mass-balance approach on coal, and they assumed that only $H_2O$ and $CO_2$ were given off until high-volatile bituminous rank was reached when methanogenesis began. However, the observed changes in H/C and O/C ratios during coalification can be explained equally well using many different ratios of $H_2O$, $CO_2$, and $CH_4$ generated as well as assuming that longer chain hydrocarbon gases are also produced, an assumption that is supported by laboratory pyrolysis experiments (Saxby and others, 1986). In addition, more hydrocarbons can be generated if it is assumed that water in the system can act as a hydrogen donor (Lewan, 1992). Laboratory pyrolysis experiments have shown that coals generate methane to thermal maturities of at least $R_o$ 4.0 percent (Higgs, 1986). For a recent summary, see Levine (1993).

Table 2 shows when critical vitrinite reflectance levels were achieved by Type-III organic matter 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 Southwestern Wyoming Province (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). Levine (1993) cites compelling evidence that oil is generated by humic coals throughout the bituminous stage of coalification, but the oil remains trapped in the molecular structure of the coal until debitumenization of coal begins at an $R_o$ of 1.0 to 1.1 percent. Time-temperature modeling indicates that the $R_o$ levels of 0.5, 0.8, 1.1, and 1.35 percent were reached at the base of the Mesaverde TPS (top of the Baxter Shale) in the Eagles Nest well at 66, 59, 54, and 50 Ma and in the Adobe Town well at 63, 54, 50, and 48 Ma. In the Texas Pacific No. 1 Bear well, an $R_o$ of 0.5 and 0.8 percent were reached at 67 and 7 Ma respectively, while an $R_o$ of 1.1 percent was never reached in the well. Thermal maturity levels of 0.6, 0.8, 1.1, and 1.35 percent were reached at the top of the Mesaverde TPS in the Eagles Nest well at 62, 52, 46, and 29 Ma and in the Adobe Town well 56, 50, 46, and 44 Ma (table 1). In the No. 1 Bear well, an $R_o$ of 0.5 was reached by 12 Ma.

Kinetic modeling predicts timing and the amount of hydrocarbons generated by kerogen by using laboratory experiments such as hydrous pyrolysis. Table 3 summarizes the results of the kinetic modeling of Roberts and others (Chapter 3, this CD–ROM) for the three 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

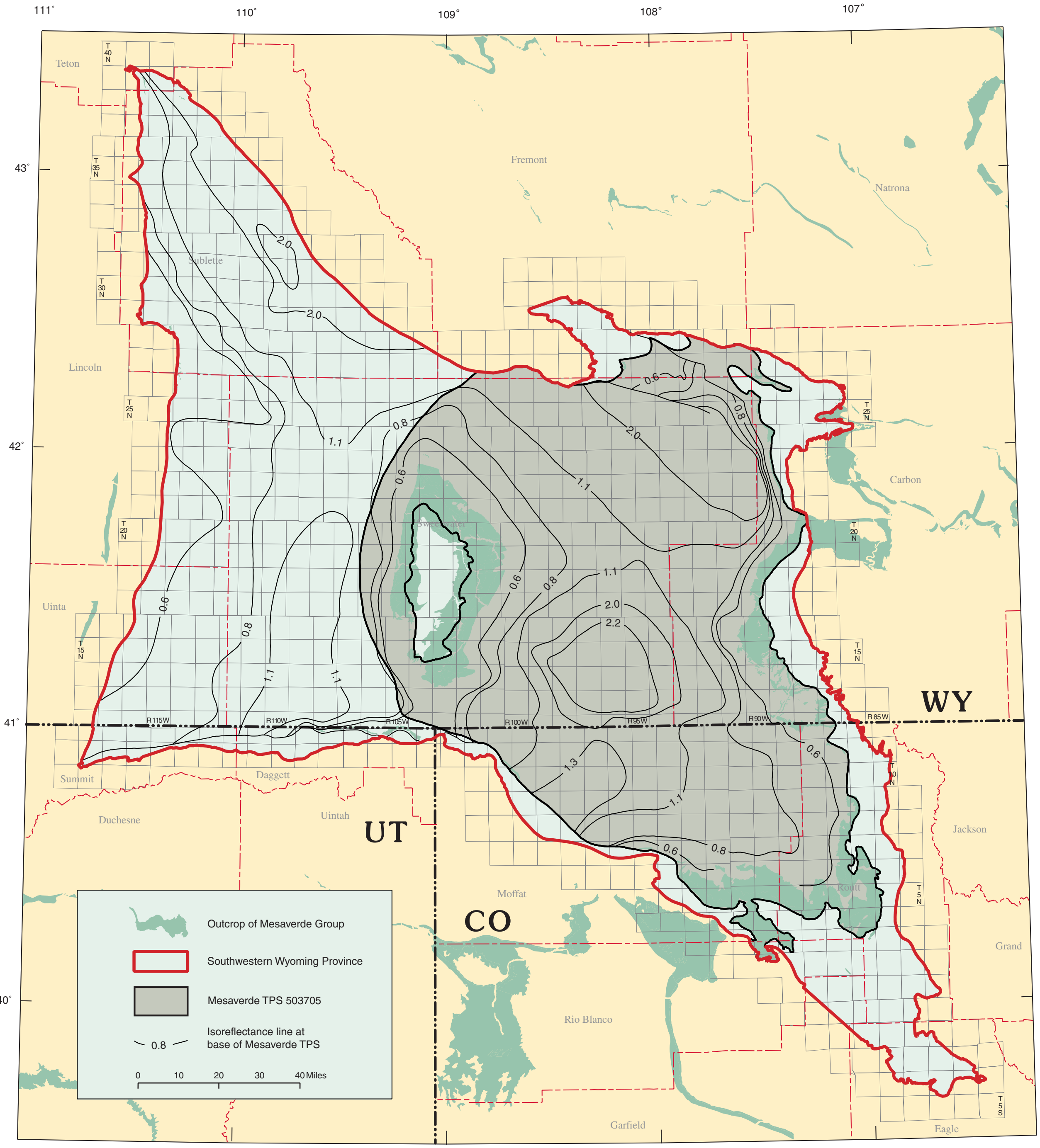


**Figure 5.** Variations in vitrinite reflectance in percent $R_o$ at the base of the Mesaverde Total Petroleum System, Southwestern Wyoming Province.

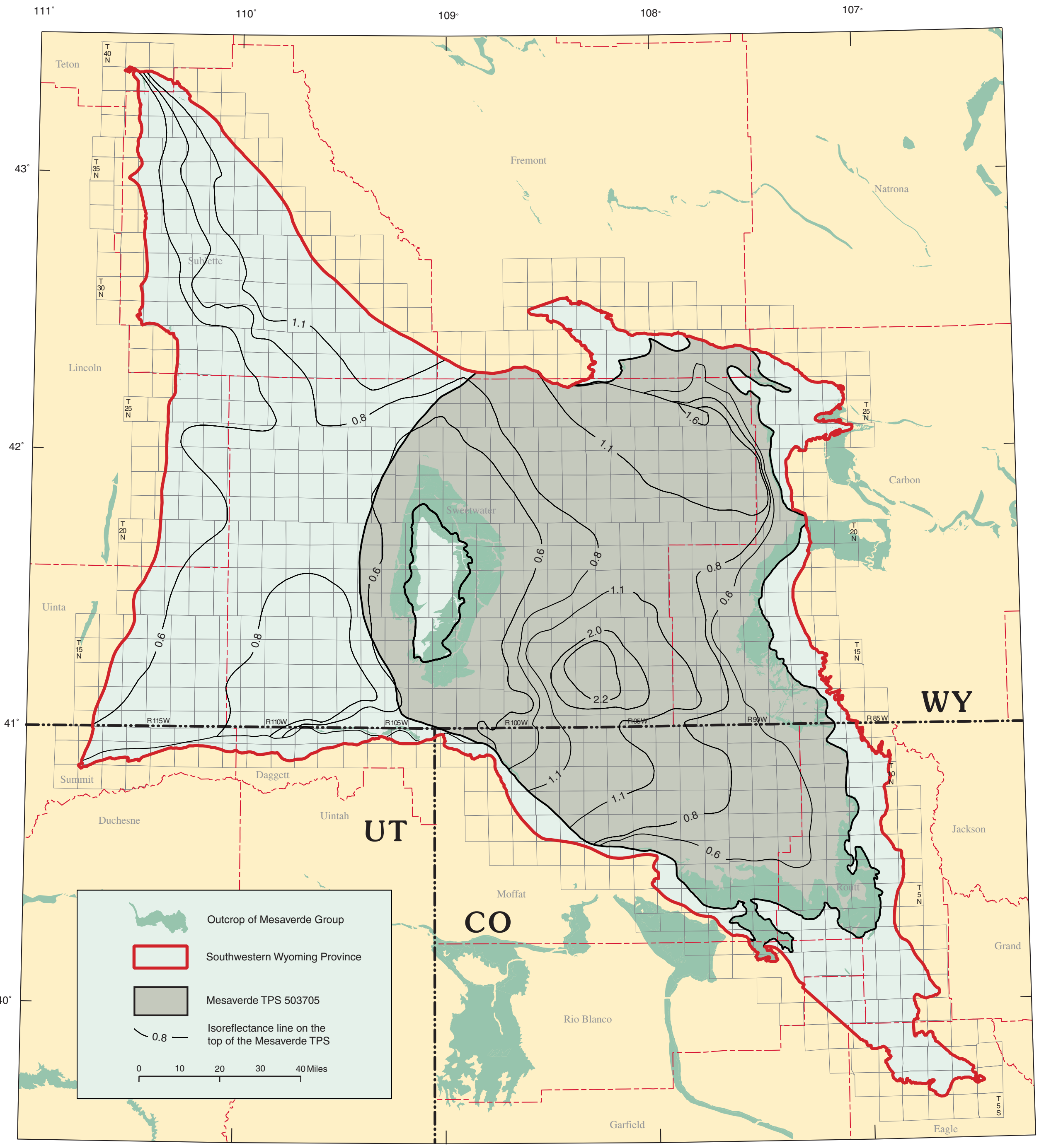


**Figure 6.** Variations in vitrinite reflectance in percent $R_o$ at the top of the Mesaverde Total Petroleum System.

**Table 2.** Years before present (BP) when the vitrinite reflectance ($R_o$) levels of 0.5, 0.6, 0.8, 1.1, and 1.35 were reached by Type-III organic matter in key wells in the Southwestern Wyoming Province using time-temperature modeling. For locations of these wells see figure 1. From Roberts and others (Chapter 3, this CD–ROM). [BP, before present]

| Vitrinite reflectance ($R_o$) level, in percent | 0.5 | 0.6 | 0.8 | 1.1 | 1.35 | 2 |
|---|---|---|---|---|---|---|
| **Adobe Town** | Years BP | Years BP | Years BP | Years BP | Years BP | Years BP |
| Base of Mesaverde Group | 63 | 59 | 54 | 50 | 48 | 44 |
| Top of Mesaverde Group | 56 | 54 | 50 | 46 | 44 | 36 |
| **Eagles Nest** | Years BP | Years BP | Years BP | Years BP | Years BP | Years BP |
| Base of Mesaverde Group | 66 | 64 | 59 | 54 | 50 | 32 |
| Top of Mesaverde Group | 62 | 59 | 52 | 46 | 29 | |
| **Bear 1** | Years BP | Years BP | Years BP | Years BP | Years BP | Years BP |
| Base of Mesaverde Group | 67 | 63 | 7 | | | |
| Top of Mesaverde Group | 12 | | | | | |

**Table 3.** Years before present (BP) for the onset, peak, and end of oil and gas generation by Type-II organic matter for selected wells in the Southwestern Wyoming Province using the kinetic model of Roberts and others (Chapter 3, this CD–ROM). For locations of these wells see figure 1. [BP, before present]

| | Years BP to obtain vitrinite reflectance level | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Oil generation | | | | | | Gas generation | | | | | |
| Key wells | Start (Ma) | (%$R_o$) | Peak (Ma) | (%$R_o$) | End (Ma) | (%$R_o$) | Start (Ma) | (%$R_o$) | Peak (Ma) | (%$R_o$) | End (Ma) | (%$R_o$) |
| **Adobe Town** | | | | | | | | | | | | |
| Base of Mesaverde Group | 55 | 0.67 | 51 | 0.93 | 49 | 1.19 | 45 | 1.67 | 41 | 2.39 | 18 | 2.98 |
| Top of Mesaverde Group | 52 | 0.69 | 48 | 0.92 | 46 | 1.13 | 41 | 1.73 | 5 | 2.44 | | |
| **Eagles Nest** | | | | | | | | | | | | |
| Base of Mesaverde Group | 61 | 0.64 | 54 | 0.93 | 48 | 1.15 | 39 | 1.63 | | | | |
| Top of Mesaverde Group | 56 | 0.69 | 49 | 0.92 | 44 | 1.13 | No gas | | | | | |
| **Bear 1** | | | | | | | | | | | | |
| Base of Mesaverde Group | 44 | 0.69 | | | | | No gas | | | | | |
| Top of Mesaverde Group | No oil | | | | | | No gas | | | | | |

thermal maturity as oil is cracked to gas. In kinetic modeling of Type-II organic matter there is no direct correlation between hydrocarbon generation and changes in $R_o$; thus the onset, peak, and end of oil and gas generation occur over a range of $R_o$ values.

Using the model, oil generation began in the Mesaverde TPS at an $R_o$ of 0.64–0.69 percent, peaked at an $R_o$ of 0.92–0.93 percent, and ended at an $R_o$ of 1.13–1.19 percent. Gas generation in the TPS begins at an $R_o$ of 1.63–1.73 percent, peaked at an $R_o$ of 2.39–2.44 percent, and ended at an $R_o$ of 2.98 percent. The onset, peak, and end of oil generation in coal beds near the top of the Mesaverde, which are thought to have produced most of the oil in the TPS (Garcia-Gonzalez and Surdam, 1992), were reached at 52, 48, and 46 Ma in the Adobe Town well, and at 56, 49, and at 44 Ma in the Eagles Nest well. No oil has been generated by these coals in the Bear well. Oil in these coalbeds would have cracked to gas in only the Adobe Town well where the onset and peak of gas generation occurred at 41 and 5 Ma. The onset, peak, and end of oil generation in coals at the base of the Mesaverde Group occurred at 55, 51, and 49 Ma in the Adobe Town well, and at 61, 54, and 48 Ma in the Eagles Nest well. Oil generation began 44 Ma in the Bear well and never reached peak generation. The onset, peak, and end of gas generation in these coal beds through the cracking of oil in the Adobe Town well were reached at 45, 41, and 18 Ma (fig. 7, table 1). Gas generation began at the base of the Mesaverde in the Eagles Nest well at 39 Ma and has not yet peaked.

Thus, gas generation through the cracking of oil generated by Type-II organic matter may have contributed significant amounts of gas recently in the deepest parts of the Mesaverde TPS in the Great Divide and Washakie Basins. Thermal maturities are at present too low in the Texas Pacific No. 1 Bear well along the east margin of the San Wash Basin

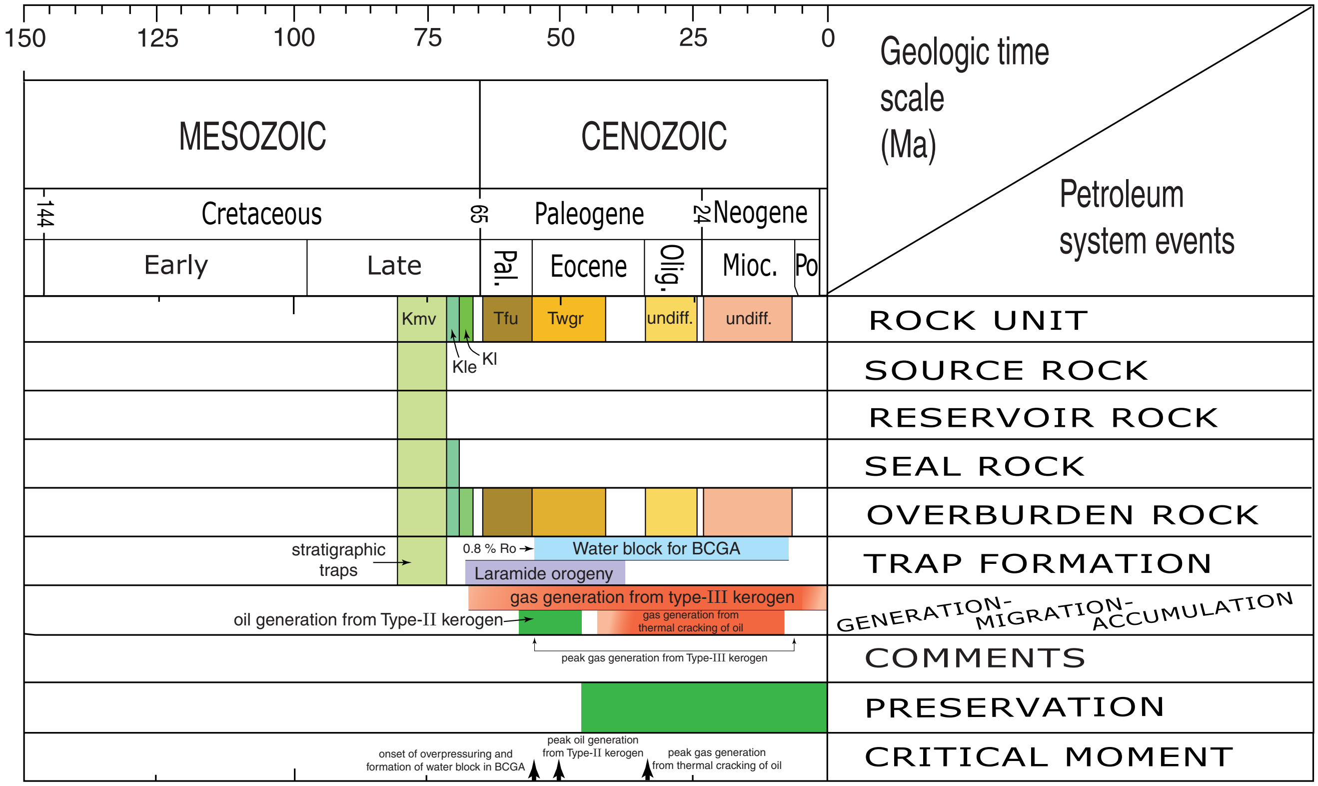


**Figure 7.** Petroleum system events chart showing interpreted timing of elements and processes related to hydrocarbon generation and accumulation in the Mesaverde Total Petroleum System (503705). Water block refers to hydrocarbon trapping by capillary seal. The timing of hydrocarbon generation is from Roberts and others (Chapter 3, this CD–ROM). Events chart format modified from Magoon and Dow (1994). Kmv=Mesaverde Group, Kle=Lewis Shale, Kl=Lance Formation, Tfu= Fort Union Formation, Twgr=Wasatch and Green River Formations, undiff.=undifferentiated, BCGA=basin-centered gas accumulation, Ma=millions of years before present, Pal.=Paleocene, Olig.=Oligocene, Mio.=Miocene, Po=Pliocene.

for the cracking of oil in Type-II source rocks. The possibility that the cracking of oil trapped in coal and organic-rich shales contributed a significant amount of gas to the Mesaverde TPS was suggested by Garcia-Gonzalez and Surdam (1992) and is supported by the presence of a significant percentage of liptinitic, or hydrogen-rich, oil-generating macerals in coals from the Mesaverde and Lance Formations in the Southwestern Wyoming Province.

## Hydrocarbon Migration

Figure 7 is a petroleum system events chart summarizing hydrocarbon generation and accumulation in the Mesaverde TPS. Hydrocarbons can migrate laterally through persistent porous units or vertically through faults and fractures. Coals and organic-rich shales in the Mesaverde Group are thought to be the principal source of oil and gas in both conventional and unconventional gas-assessment units in the Mesaverde TPS, including the large amounts of oil produced from conventional stratigraphic traps at Patrick Draw, Table Rock, and Desert Springs fields on the east flank of the Rock Springs uplift, along the Wamsutter arch (MacGowan and others, 1992, 1993; Garcia-Gonzalez and Surdam, 1992, 1995; Garcia-Gonzalez and others, 1993). Gas in both conventional and unconventional assessment units in the Mesaverde TPS could have been formed directly from kerogen in coals and organic-rich shales or from the cracking of oil. Coalbed gas is thought to be largely indigenous, having formed by the breakdown of kerogen and oil within the coalbeds.

Coals have a substantial capacity to store hydrocarbon gases and liquids in micropores and cleats, and adsorbed within its molecular structure. Thus, large-scale migration from coal beds into sandstone reservoir rocks would not have occurred at the onset of hydrocarbon generation but later, when the capacity to store hydrocarbons was exceeded. The storage 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. In addition, 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. Major expulsion of hydrocarbons by coal probably begins at the onset of devolatilization ($R_o$ 0.90–1.1 percent) when H/C ratios in coalbeds turn sharply downward (Levine, 1993).

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 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.

Thermal maturities of the Almond coals within the Patrick Draw, Table Rock, and Desert Springs conventional oil fields vary from 0.60 to 0.80 percent $R_o$ or marginally mature for the generation of oil and below the $R_o$ of about 0.90 percent needed to expel oil. The fields are updip from both the Washakie and Great Divide Basins; thus, oil expelled from coalbeds in the deep troughs of either of these basins could have migrated into these fields. An $R_o$ of 0.90 percent corresponds approximately to peak oil generation in the kinetic model for Type-II organic matter, which was reached by Almond coals in the Deep Washakie Basin at about 48 Ma and in the deep Great Divide Basin about 49 Ma or during the middle Eocene.

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 can only occur once microfractures form. Thus, oil from organic-rich shales in the Almond Formation could conceivably have migrated into reservoir rocks in the early Eocene when thermal maturities were somewhat lower than an $R_o$ of 0.90 percent in the deep troughs of the adjacent basins.

A better understanding of the origin and migration of gas in the Mesaverde TPS in the Southwestern Wyoming Province is hindered by a lack of detailed studies showing variations in chemical and isotopic compositions of gases in the basin. Until such studies become available, analogs from other Rocky Mountain basins, where detailed studies on variations in gas compositions have been published, have to be used. The Upper Cretaceous and lower Tertiary section in these more studied Rocky Mountain basins is similar to that in Southwestern Wyoming Province, lending some validity to these comparisons.

In the Uinta Basin of eastern Utah and western Colorado, Rice and others (1992) found that nonassociated gases produced from Upper Cretaceous Mesaverde Group and the Tertiary Wasatch and Green River Formations at Natural Buttes field were isotopically similar over depths from 4,210 to 9,332 ft. Isotopic ratios suggest that all of the gases were generated by Type-III organic matter at vitrinite reflectance values ranging from 1.0 to 1.5 percent, the thermal maturity of coaly Type-III source rocks in the lower part of the Mesaverde underlying the field. Thus, all of the reservoirs in the field were probably charged by vertical migration of gas through faults and fractures from the lower part of the Mesaverde Group. Extensive lateral migration of fluids was apparently inhibited by the lenticular nature of sandstones in the interval. In contrast, Rice and others (1992) found that oil and associated gases at Red Wash field were probably generated by Type-I lacustrine-source rocks much deeper in the basin, near Altamont-Bluebell field about 40 to 59 mi to the northwest. This long-range lateral migration was aided by the blanketlike geometry of marginal lacustrine sandstones and limestones in the Eocene Green River Formation.

Largely vertical migration of gases from Type-III source rocks in the lower part of the Mesaverde Group into overlying sandstone reservoir rocks has also been documented in the Piceance Basin of western Colorado (Johnson and Rice, 1990; Johnson and others, 1994) and the Wind River Basin of Wyoming (Johnson and Rice, 1993). Again, the lenticular nature of sandstones in these intervals probably inhibited long-range lateral migration. In the Piceance Basin, Johnson and Rice (1990) and Johnson and others (1994) found methane to be isotopically similar through many thousands of feet of Upper Cretaceous and lower Tertiary continental rocks containing mainly lenticular sandstone reservoirs in three areas of the basin; however, the isotopic composition of the methane was different in these three areas. These differences could be directly related to variations in thermal maturities in coaly source rocks in the underlying lower part of the Mesaverde. This close relationship between methane throughout a thick stratigraphic interval of lenticular reservoirs and thermal maturities in the immediate underlying Type-III source rocks is convincing evidence for largely vertical rather than lateral migration. Similarly, gases through many thousands of feet of Upper Cretaceous and lower Tertiary continental rocks in two areas of the Wind River Basin were found to be isotopically similar (Johnson and Rice, 1993; Johnson and others, 1994). Vertical migration of gases from Type-III source rocks 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).

In the Piceance Basin of western Colorado, the marginal marine Rollins and Trout Creek Sandstone Members of the Iles Formation is found throughout much of the Piceance Basin and appears to have also acted as a conduit for the lateral migration of fluids (Johnson, 1989). The Rollins and Trout Creek, a single sandstone with different names in different parts of the basin, is unique in that it appears to be predominantly water-wet, even within basin-centered accumulations where little water is produced from adjacent lenticular sandstones. Paleogeographic reconstructions by Johnson and Nuccio (1986) and Johnson (1989) indicate that the Rollins and Trout Creek has been exposed on the margins of the Piceance Basin since Eocene time, thus providing a conduit for hydrocarbons to move out of the basin and water to move in.

Lenticular sandstones are found throughout the nonmarine continental intervals in the Rock Springs and Allen Ridge Formations and the lower part of the Almond Formation, while laterally persistent marine bar sandstones are found in the upper Almond and Rock Springs and Allen Ridge Formations where they interfinger with marine shales. The Ericson Sandstone is of nonmarine origin but is very sandy and may generally act regionally as a single persistent sandstone or series of persistent sandstones. Using other Rocky Mountain basins as an analog, largely vertical migration of gas probably took place in intervals of largely lenticular sandstones. Extensive lateral migration of oil and gas probably took place in the more persistent “blanketlike” sandstones. The “blanketlike” nature of the upper Almond Formation bar sandstones almost certainly aided the lateral migration of hydrocarbons from the deeper, more mature areas of the Washakie and Great Divide Basins into these sandstones at Patrick Draw, Table Rock, and Desert Springs fields along the east flank of the Rock Springs uplift. Blanketlike marginal marine sandstones in the Rock Springs Formation and the regionally extensive nonmarine Ericson Formation also may have acted as conduits for the lateral migration of oil and gas as well as water, but there is too little drill-hole information at present to prove this. Pathways where oil and gas can escape to the surface and surface water can migrate downward are created in areas where persistent sandstones crop out, and it is likely that sandstones in these areas will contain mainly water and little oil and gas.

## Hydrocarbon Reservoir Rocks

Reservoir rocks are fluvial sandstones, found throughout the Mesaverde Group, marginal marine sandstones in the Almond Formation and lower part of the Rock Springs Formation, and coalbeds throughout the Mesaverde Group.

The Campanian-age Rock Springs, Allen Ridge, Iles, and Williams Fork Formations of the Mesaverde Group are a complex interval deposited in marginal marine and coastal-plain settings along the western margin of the Cretaceous interior seaway. Shorelines trended generally northeast during a prolonged period of nearly 5 million years early in the deposition of the Rock Springs Formation. The shoreline transgressed and regressed across a limited area of the Great Divide, Washakie, and Bridger Basins (Roehler, 1990), and as many as 15 shoreline sequences were deposited during this period (Roehler, 1990). This was followed by southward progradation of a major delta that began in the northern part of the Great Divide Basin and eventually pushed the shoreline southeastward as far as the northern part of the Sand Wash Basin (Roehler, 1990, his plate 2). The Haystack Mountains Formation was deposited during this deltaic progradation (figs. 2–4). In the southern part of the Rock Springs uplift the shoreline still maintained a northeast trend in about the same position throughout the development of this delta. Potential reservoir rocks in the assessment unit include marginal marine sandstones, fluvial sandstones, and coal.

Coal-forming environments developed landward of the shoreline behind laterally persistent delta-front sandstones and in delta plain and abandoned delta lobe settings. The thickest and most persistent coals accumulated on the delta-front sandstones (Levey, 1985). The relatively stationary position of the shoreline for an extended period of time created a thick accumulation of coal along a fairly narrow, northeast-trending belt in the Rock Springs Formation (Tyler and others, 1995, their fig. 29). Approximately time-equivalent thick, early Campanian-age coals are present in the Mesaverde Formation to the north in the Wind River Basin along a narrow, north-trending zone landward of a relatively stationary shoreline (Johnson and others, 1996, their fig. 24) and to the south into the western part of the Uinta Basin, in the Blackhawk Formation (Fisher and others, 1960).

The fluvial Ericson Sandstone overlies the Rock Springs Formation and was deposited during maximum regression of the Cretaceous seaway in southwestern Wyoming prior to the Lewis transgression. The Ericson was deposited during a period of uplift and erosion throughout western Wyoming (Gill and Cobban, 1966), and much of the sediment in the Ericson is probably reworked from older Cretaceous rocks in that area. Beveling of underlying rocks is well documented along the Moxa arch in the western part of the Green River Basin (Roehler, 1990), west of the Mesaverde TPS, and in the Lost Soldier anticline area east of the Mesaverde TPS (Reynolds, 1976). The Ericson is subdivided into three parts in ascending order: the Trail Member, the informal Rusty zone, and the Canyon Creek Member. The Trail and Canyon Creek Members consist largely of highly amalgamated fluvial sandstone whereas the Rusty zone consists of more isolated channel sandstone bodies in fine-grained alluvial-plain deposits (Pederson and Steel, 1999). The Trail Member unconformably overlies the Rock Springs Formation in the western part of the Mesaverde TPS but becomes conformable with and interfingers with the Allen Ridge Formation to the east (fig. 3). The overlying Rusty zone also appears to grade to the east into the Allen Ridge Formation (Roehler, 1990, his plate 2).

The most significant unconformity in duration, amount of section truncated, and regional extent in the Ericson is the unconformity at the base of the Canyon Creek Member (fig. 3), which truncates rocks to the upper part of the Hilliard Shale over the Moxa arch, west of the Mesaverde TPS. The Canyon Creek represents maximum eastward regression during Ericson deposition. It correlates with the Pine Ridge Sandstone along the eastern margin of the Great Divide and Washakie Basins and appears to correlate with the regressive Twentymile Sandstone Member of the Williams Fork Formation in the Sand Wash Basin (fig. 4).

The Almond Formation generally varies from about 250 to 500 ft thick and was deposited in a marginal marine and lower coastal setting during the transgression of the Lewis seaway into the eastern part of the Southwestern Wyoming Province in early Maastrichtian time. Workers in the past have subdivided the Almond into various informal units of local extent (see for example, Weimer, 1965; Martinsen and others, 1995; Sturm and others, 2001); but all of these previous workers recognized two general intervals: (1) an upper Almond interval that contains laterally persistent marginal marine sandstones interbedded with tongues of marine Lewis Shale, and (2) a lower or main Almond interval that consists of lenticular sandstones nonmarine shales and mudstones, and coal. The Almond was deposited during the westward expansion of a large, U-shaped embayment in the Cretaceous seaway that ultimately covered much of the eastern half of the Southwestern Wyoming Province. Shoreline trends during deposition of the Almond varied from east and northeast in the northern part of the Great Divide Basin to northwest in the Sand Wash Basin (Weimer, 1965; Roehler, 1990; Hendricks, 1994). The Almond, as a whole, becomes progressively younger toward the west; thus, the upper Almond at any given locality grades to the west into nonmarine lower Almond and to the east into marine Lewis Shale. Syndepositional faulting has compartmentalized upper Almond marine bar sandstones in parts of the Washakie Basin (Martinsen, 1998).

## Hydrocarbon Traps and Seals

The marine Lewis Shale seal overlies the entire Mesaverde TPS, inhibiting the vertical migration of gas out of the TPS. Less extensive shale and mudstone seals are also present throughout the nonmarine intervals in the Mesaverde TPS. Oil is trapped in the Almond Formation at Patrick Draw field by the updip pinch-out of marginal marine bar sandstones into fine-grained nonmarine rocks (Weimer, 1966). The pinch-out of these bar sandstone units before reaching outcrop may also inhibit the downward migration of surface water, thus helping to preserve the continuous-type gas deposits in these sandstones. The overall trapping mechanism for continuous-type accumulations, such as the continuous gas accumulation that is present in the Mesaverde TPS in the more thermally mature ($R_o$ greater than 0.80 percent) parts of the TPS, is thought to be a capillary seal or water block (Masters, 1979).

## Assessment Unit Definition

The Mesaverde Total Petroleum System was divided into four assessment units: (1) Mesaverde Conventional Oil and Gas Assessment Unit (50370501); (2) Almond Continuous Gas Assessment Unit (50370561); (3) Rock Springs–Ericson Continuous Gas Assessment Unit (50370562); and (4) Mesaverde Coalbed Gas Assessment Unit (50370581).

A single, overpressured continuous gas accumulation is present in the Mesaverde TPS. This accumulation cuts across stratigraphic boundaries including all stratigraphic units in the Mesaverde Group (Law, 1984). The vast majority of gas produced from this accumulation to date, however, has been from the Almond Formation, largely from the upper Almond marine bar sandstones, whereas little gas has been produced from the underlying Ericson and Rock Springs Formations, although these units contain far more gas in place than the Almond (Law and others, 1989). A total of 1,086 wells perforated in the Almond are projected to produce more than the minimum of 0.02 billion cubic feet of gas (BCFG) (Appendix A) whereas only 97 wells perforated in the underlying Ericson and Rock Springs Formations are projected to exceed this minimum (Appendix B), and most of these 97 wells are coproducing out of the Almond Formation. Because of these differences in production characteristics, the Almond Formation was assessed separately from the underlying Ericson and Rock Springs Formations.

Law (1984) found that an $R_o$ of about 0.80 percent approximately corresponded to the top of the overpressured continuous accumulation in the Southwestern Wyoming Province, and this thermal maturity level is used here to define the limits of the accumulation in both the Almond Continuous Gas Assessment Unit (50370561) and the Rock Springs–Ericson Continuous Gas Assessment Unit (50370562). An exception to this criterion is a limited part of the eastern Washakie Basin where the boundary of the Almond Continuous Assessment Unit was extended into slightly lower levels of thermal maturity in order to include all production at Robber's Gulch and Blue Gap fields (fig. 8) which are considered to be continuous in nature.

## Assessment Results

### Almond Continuous Gas Assessment Unit (AU 50370561)

The Almond Continuous Gas Assessment Unit (50370561) covers more than 3.3 million acres in the deeper areas of the Mesaverde TPS (fig. 8). It produces mainly gas and gas liquids. The great majority of production from the Almond Continuous Gas Assessment Unit to date has been from laterally continuous marine bar sandstones in the upper Almond. Tidal channel sandstones within these bar sandstones have the greatest porosity and permeability and are the most productive facies in the Almond (Sturm and others, 2001).

Lenticular sandstones in the lower part of the Almond have increasingly contributed to Almond production (Horn and Schrooten, 2001), although these sandstones are typically less productive than the overlying marine bar sandstones (Sturm and others, 2001; Horn and Schrooten, 2001). Low recoveries and excessive water production have impeded attempts to produce gas from these lenticular sandstones at Siberia Ridge field (Sturm and others, 2001), but Echo Springs–Standard

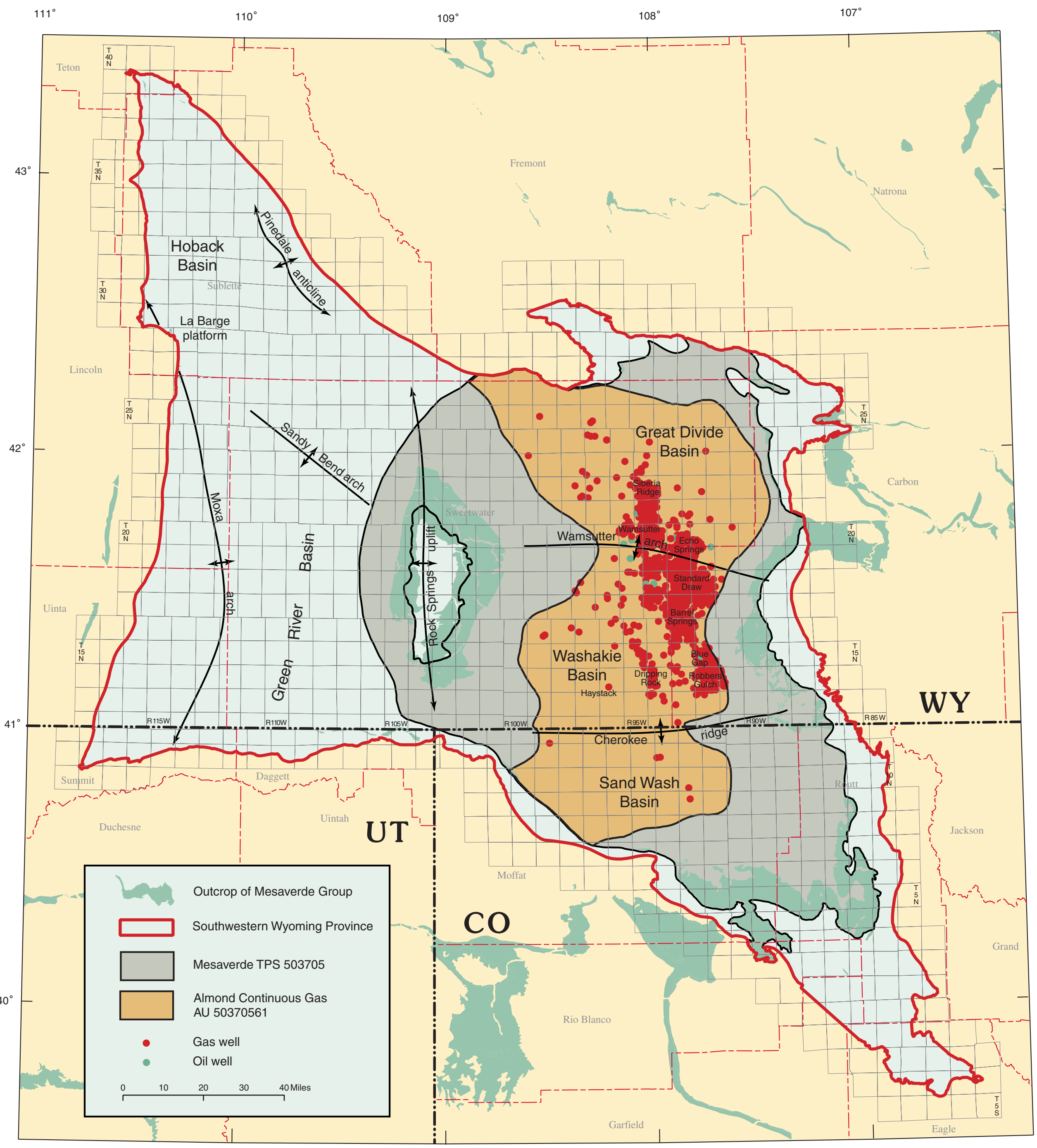


**Figure 8.** Extent of the Almond Continuous Gas Assessment Unit (AU 50370561) in the Mesaverde Total Petroleum System, Southwestern Wyoming Province. The assessment unit is defined as that area where thermal maturities exceed a vitrinite reflectance of 0.8 percent at the top of the Almond Formation. Locations of oil and gas wells that produce from the Assessment Unit also shown.

Draw field completions in these reservoirs have met with some success (Horn and Schrooten, 2001).

Thermal maturities for the Almond in these fields ranges from $R_o$ 0.75 to 1.1 percent and would be considered to be in the "transition zone" in gas assessments of other Rocky Mountain Basins (Johnson and others, 1987, 1996, 1999; Johnson and Roberts, 2003). A transition zone is that zone between conventional and unconventional hydrocarbon accumulations where, because of marginal thermal maturities of available source rocks, gas saturation is incomplete and water problems are common. The lenticular sandstones in the Almond appear to have production characteristics similar to lenticular sandstones in the transition zones in the Uinta and Piceance Basins. The marine bar sandstones may be unique because the blanketlike geometry of these sandstones allowed extensive lateral migration of gases from more mature areas of the basin. This migration would have increased gas charge in these sandstones to greater than that typically found at these levels of thermal maturity.

The assessment unit is informally subdivided into two areas: (1) where the top of the Almond Formation is at less than 11,000 ft (fig. 9), and (2) where the top of the Almond is at greater than 11,000 ft (fig. 10). Most production from the Almond Formation to date is from areas where reservoirs are at depths of less than 11,000 ft, and most major marine bar sandstones at these depths have been extensively explored and produced. Thus, future drilling will increasingly target (1) lenticular sandstones in the lower Almond at depths of 11,000 ft or less, and (2) both marine bar sandstones in the upper Almond and lenticular sandstones in the lower Almond at depths of greater than 11,000 ft. Examining the available deep tests separately should give insight into what this future, deeper production will look like.

Figure 11 shows the distribution of estimated ultimate recoveries (EURs) for all Almond wells exceeding the minimum. Figure 12 shows EURs for Almond wells exceeding the minimum divided into thirds [Note: "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled in order to investigate how the well EURs have changed with time.] The median EUR for all wells is 0.8 billion cubic feet of gas (BCFG), whereas EURs by thirds are 0.75 BCF for the first third, 1.1 BCF for the second third, and 0.75 BCF for the third third. Factors that may have contributed to the decline in EURs may be interference among wells drilled at closer than optimal spacing and the need to complete wells in the less productive lower Almond sandstone as upper Almond bar sandstones became increasingly exploited.

The median EUR for Almond wells at less than 11,000 ft is 0.9 BCFG, whereas the median EUR for wells producing from depths greater than 11,000 ft is significantly less, 0.5 BCFG (fig. 13). EURs by thirds for the wells at less than 11,000 ft are similar to those of all Almond wells (fig. 14), largely because of the limited effect of the small number of wells completed at greater than 11,000 ft on the total EUR. Median EURs for Almond wells greater than 11,000 ft, in contrast, show a steady increase with time (fig. 15) possibly reflecting improving drilling and completion technology and a lack of interference among wells.

The estimates of minimum, median, and maximum area per cell of untested cells having potential for additions to reserves in the next 30 years are 40, 160, and 449 acres, respectively (Appendix A). These estimates are complex because of the significantly different well spacing required to drain the laterally persistent marginal marine sandstones when compared to the lenticular nonmarine fluvial sandstones.

The estimates of minimum, median, and maximum percentage of total assessment-unit area that is untested are 88, 91, and 93 percent (Appendix A). The existing major fields cover an area of about 199,680 acres or about 6.1 percent of the total assessment unit area. To determine the tested area in the Almond Continuous Gas Assessment Unit, we assumed that the Almond in these fields is completely tested and applied our estimated median drainage area (160 acres) to only the tested cells outside these fields. It was not possible to simply multiply the median drainage area with the number of tested cells to get the total drainage area because closer than optimal spacing has occurred in the two big fields, Siberia Ridge and Standard Draw. The median area that has been tested at depths of less than 11,000 ft is 11 percent, while only 1–2 percent of the area at depths of greater than 11,000 ft has been tested. The 11-percent figure for productive area in the less than 11,000-ft area was surprisingly small, but the area includes large tracts of unproductive acreage in the Sand Wash Basin and northwest part of the Great Divide Basin.

The minimum, median, and maximum percentage of untested assessment-unit area that has potential for additions to reserves over the next 30 years are 35, 52, and 76 percent, respectively. Although the highly productive marginal marine bar sandstones occupy less of the assessment unit area than these estimated percentages, lenticular sandstones in the lower Almond are present throughout most if not all of the assessment unit. These sandstones are actively being explored in Siberia Ridge and Standard Draw fields, and it is assumed that this activity will expand greatly during the next 30 years.

The minimum, median, and maximum total recovery per cell for untested cells having potential for additions to reserves in the next 30 years is 0.02, 0.9, and 20 BCFG, respectively (Appendix A). The median of 0.9 BCFG is slightly higher than the 0.7 BCFG median of the existing wells because it is assumed that future advances in technology will enhance productivity. On the downside, most of the highly productive marginal marine bar sandstones at depths of less than 11,000 ft have been drilled; thus, future exploration in this area will have to increasingly target the less productive lenticular sandstones in the lower Almond. There are still many marginal marine bar sandstones at depths of greater than 11,000 ft that have not been tested and developed, but these sandstones are

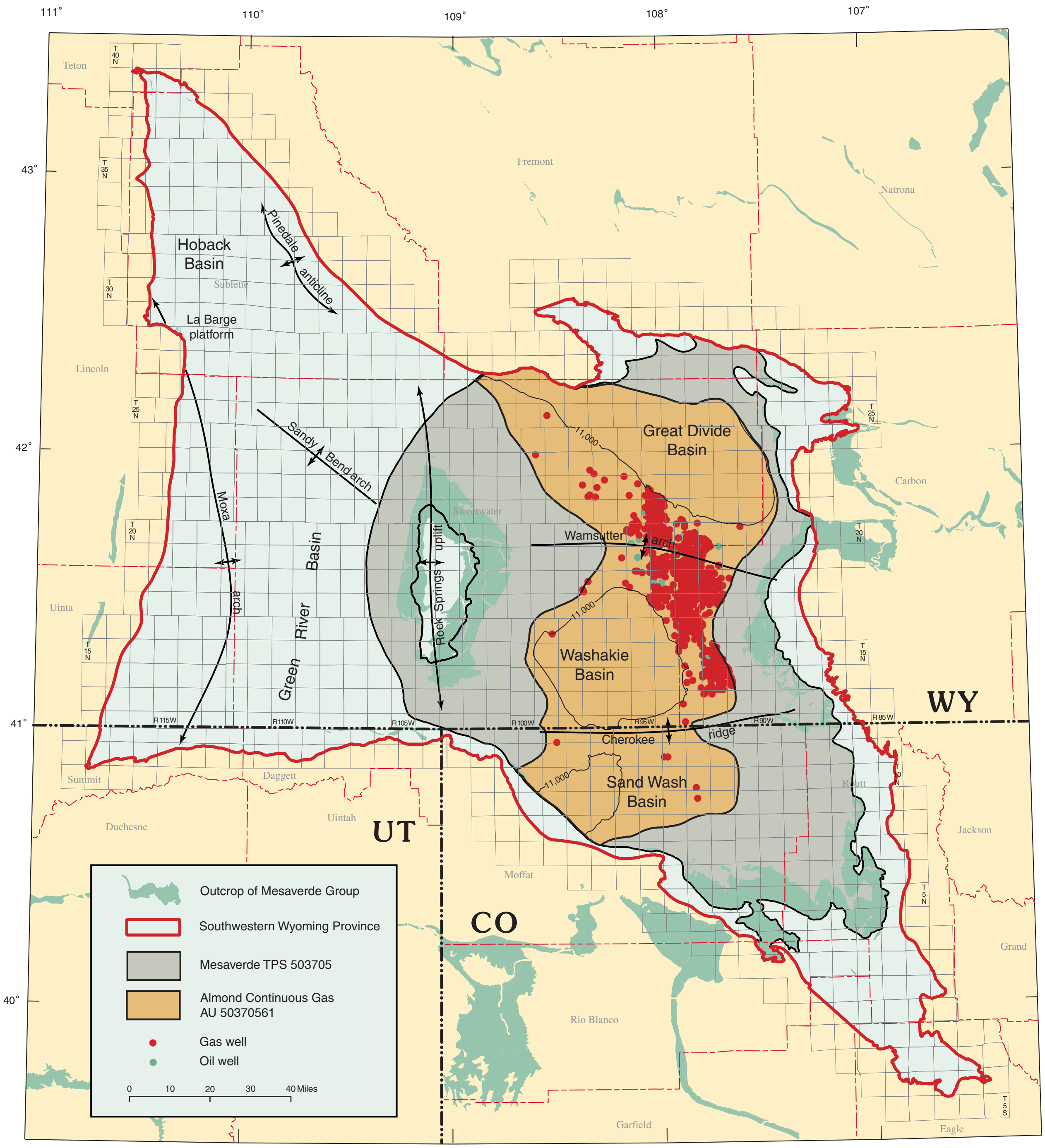


**Figure 9.** Area where the top of the Almond Continuous Gas Assessment Unit (AU 50370561) in the Mesaverde Total Petroleum System, Southwestern Wyoming Province, is at depths of less than and greater than 11,000 feet. Locations of oil and gas wells that produce from the Assessment Unit at depths of less than 11,000 feet are also shown.

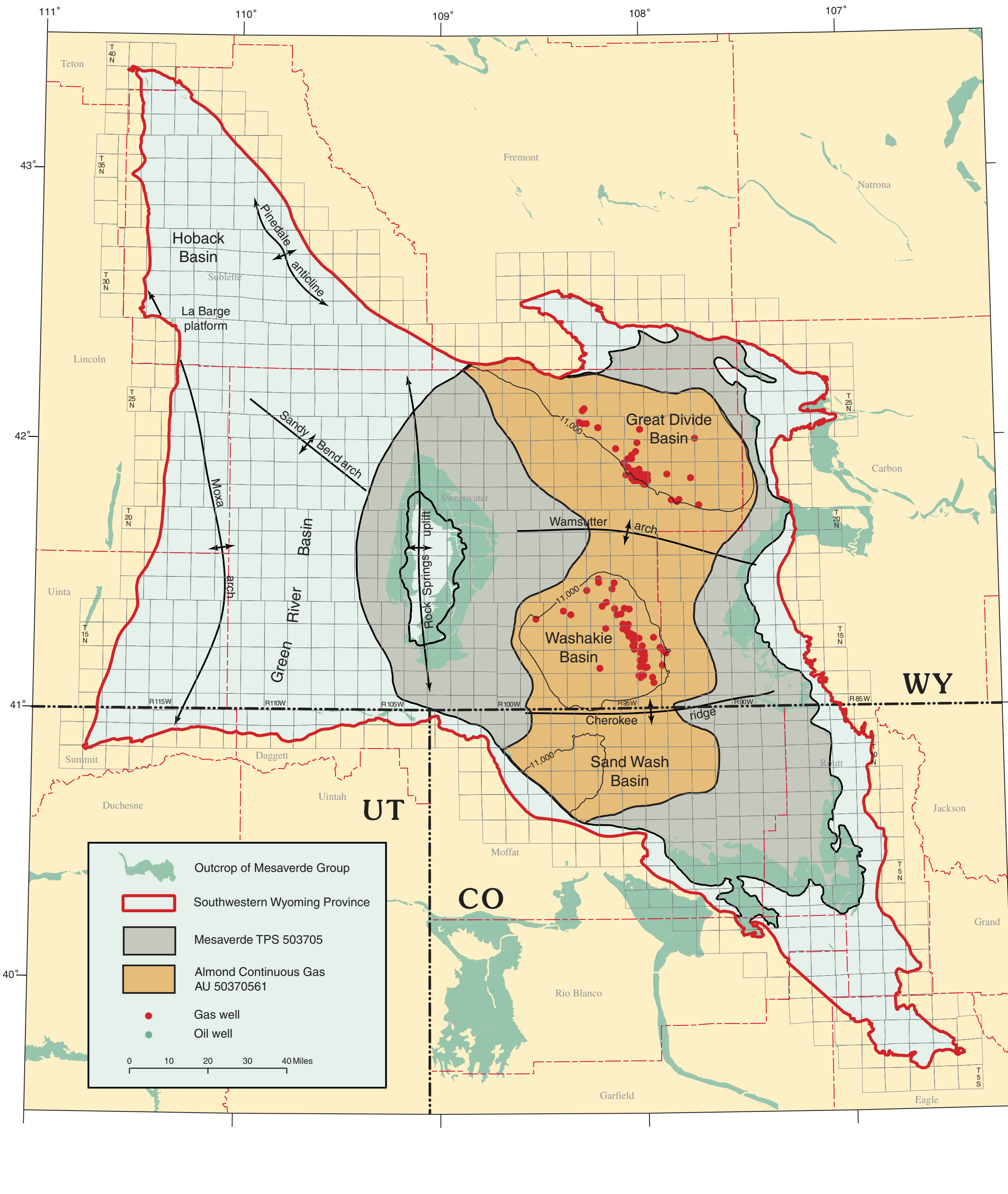


**Figure 10.** Map showing area where Almond Continuous Gas Assessment Unit (AU 50370561) in the Mesaverde Total Petroleum System, Southwestern Wyoming Province, is at depths of less than and greater than 11,000 feet or less. Locations of oil and gas wells that produce from the Assessment Unit at depths of greater than 11,000 feet are also shown.

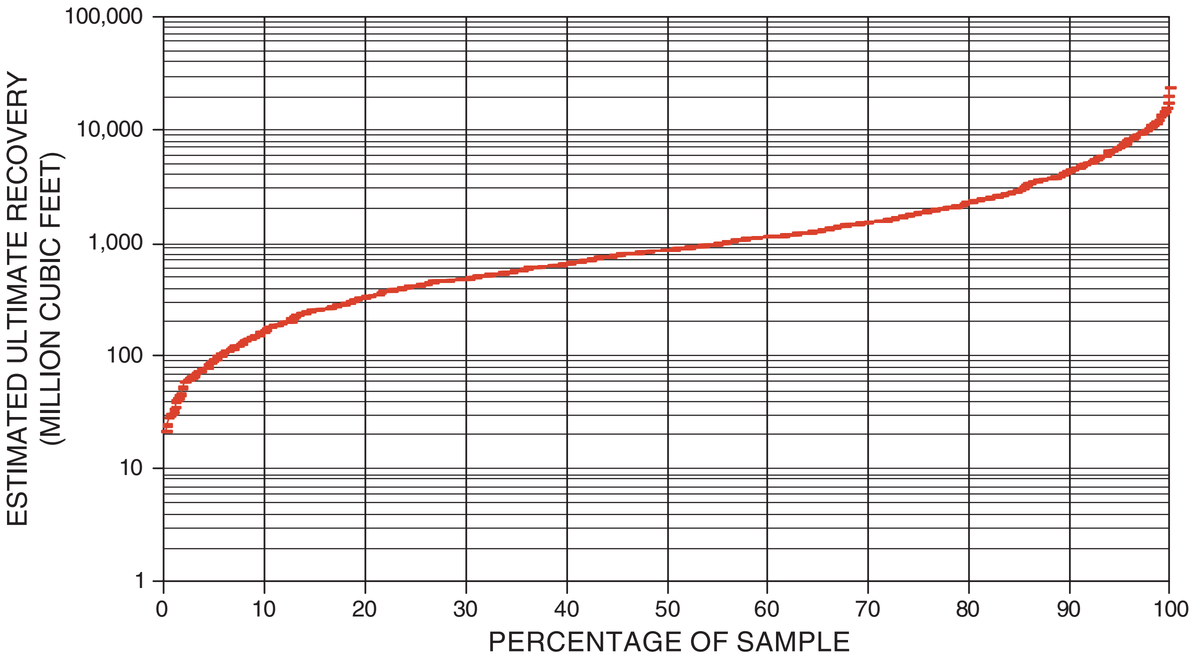


**Figure 11.** Distribution of Estimated Ultimate Recoveries (EURs) for 1,131 gas wells within the Almond Continuous Gas Assessment Unit (AU 50370561), Mesaverde Total Petroleum System, Southwestern Wyoming Province. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown.

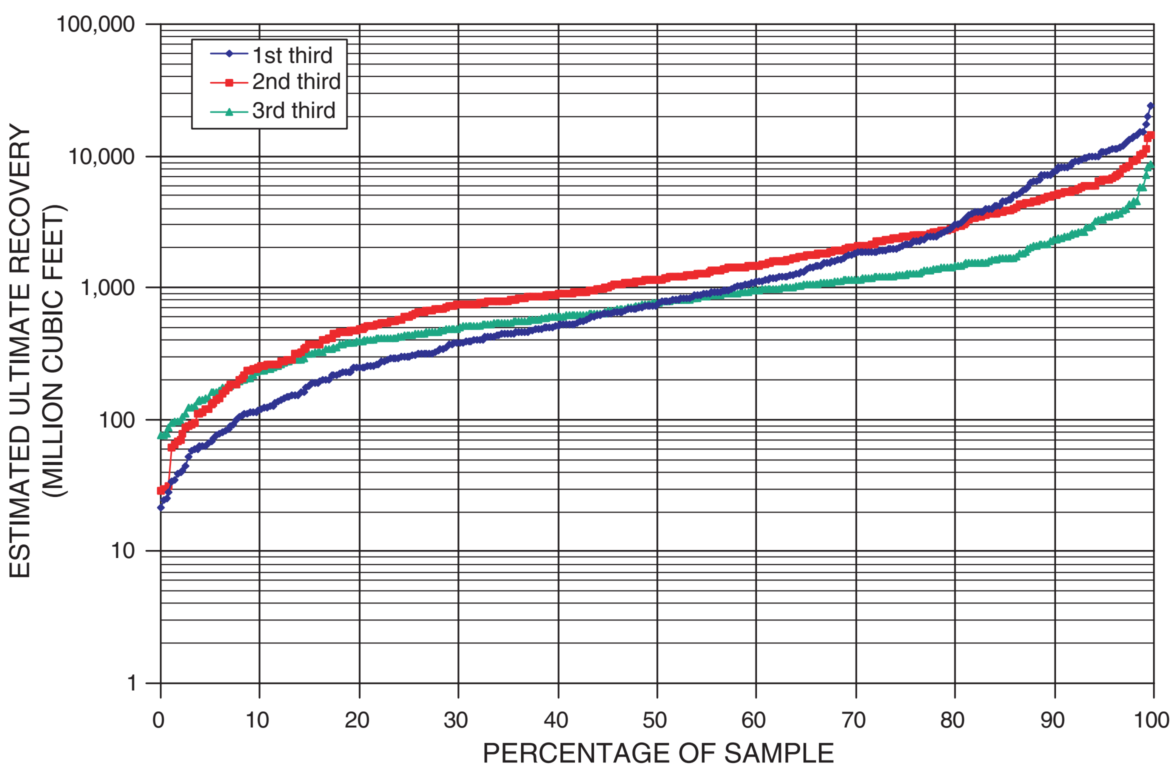


**Figure 12.** Distribution of Estimated Ultimate Recoveries (EURs) by thirds for the 1,131 gas wells within the Almond Continuous Gas Assessment Unit (AU 50370561), Mesaverde Total Petroleum System, Southwestern Wyoming Province. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled in order to investigate how the well EURs have changed with time. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown.

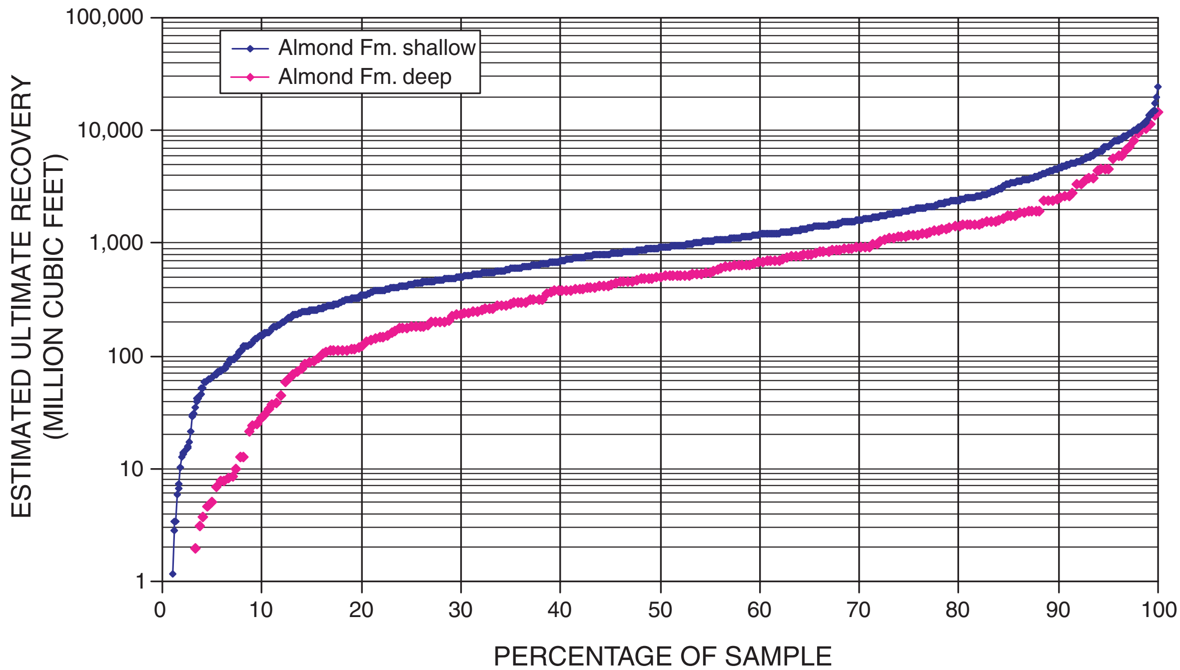


**Figure 13.** Comparison of distribution of Estimated Ultimate Recoveries (EURs) for gas wells completed at depths of less than 11,000 feet (shallow) and at depths of greater than 11,000 feet (deep) within the Almond Continuous Gas Assessment Unit (AU 50370561), Mesaverde Total Petroleum System, Southwestern Wyoming Province. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown.

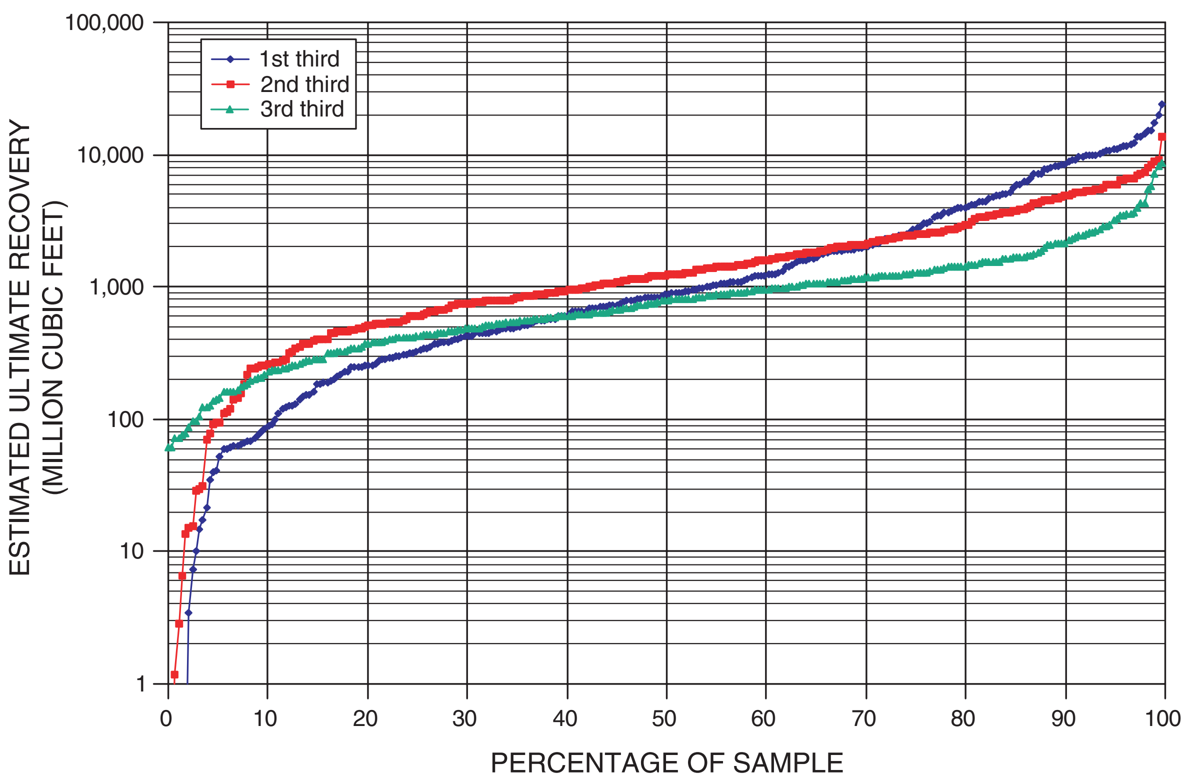


**Figure 14.** Distribution of Estimated Ultimate Recoveries (EURs) by thirds for gas wells completed at depths of less than 11,000 feet within the Almond Continuous Gas Assessment Unit (AU 50370561), Mesaverde Total Petroleum System, Southwestern Wyoming Province. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled in order to investigate how the well EURs have changed with time. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown.

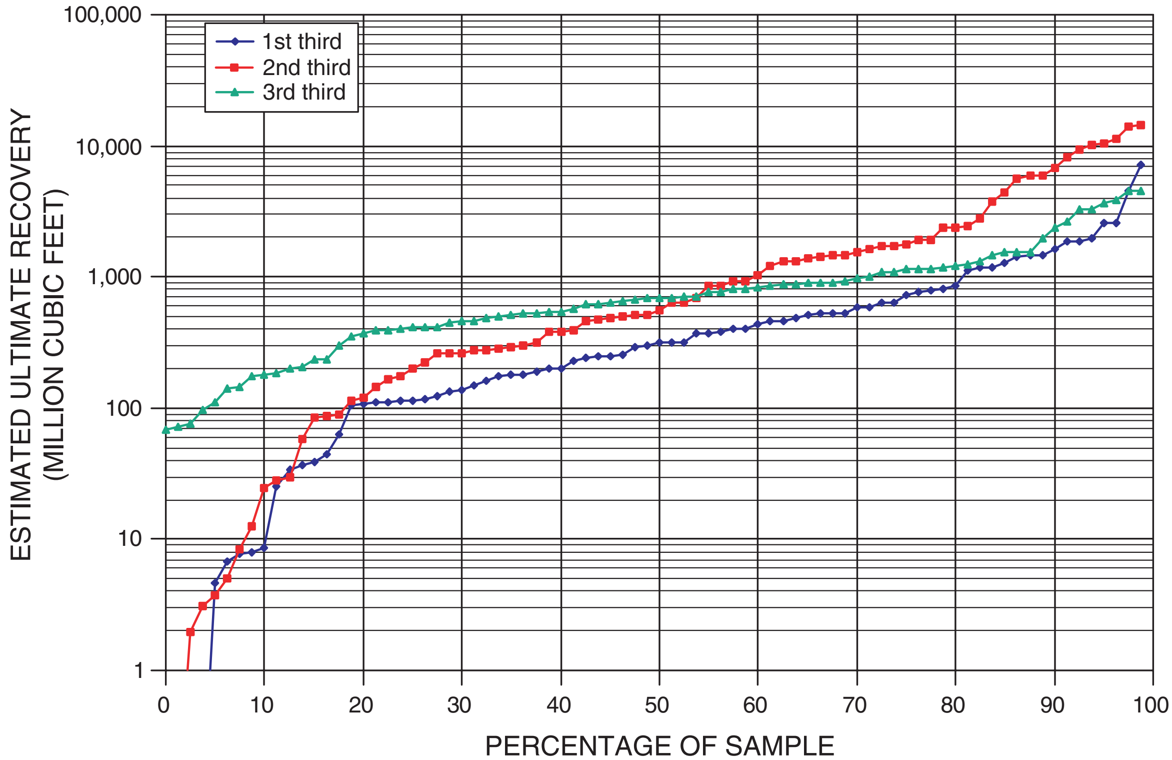


**Figure 15.** Distribution of Estimated Ultimate Recoveries (EURs) by thirds for gas wells completed at depths of greater than 11,000 feet within the Almond Continuous Gas Assessment Unit (AU 50370561), Mesaverde Total Petroleum System, Southwestern Wyoming Province. "Thirds" refers to the division into three parts of the number of wells drilled in a given area. The wells were ordered by completion date and then divided into three equal (or nearly equal) numbers of wells. Statistics were calculated for the first "third" of the wells drilled, the second "third" of the wells drilled, and the third "third" of the wells drilled in order to investigate how the well EURs have changed with time. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown.

likely to be less productive than the bar sandstones at shallower depths because of lower porosities and permeabilities. Lenticular sandstones in the lower Almond at depths of greater than 11,000 ft will also have lower porosities and permeabilities than these sandstones at shallower depths and thus will be less productive. The mean estimate of potential for additions to reserves over the next 30 years is 13.35 TCF (table 1).

## Rock Springs–Ericson Continuous Gas Assessment Unit (AU 50370562)

The boundaries of the Rock Springs–Ericson Continuous Gas Assessment Unit (50370562) were defined as that part of the Mesaverde TPS where thermal maturities at the base of the Rock Springs Formation in the Great Divide and Washakie Basins and base of the Iles Formation in the Sand Wash Basin have an $R_o$ of 0.8 percent or greater (fig. 16). The assessment unit extends farther toward the margins of the Mesaverde TPS than the overlying Almond Continuous Gas Assessment Unit (50370561) (fig. 9). It includes the Williams Fork and Iles Formations in the Sand Wash Basin.

The Rock Springs–Ericson Gas Assessment Unit (AU 50370662) covers about 4.36 million acres of the deeper parts of the Mesaverde TPS (fig. 16) and includes the Rock Springs and Ericson Formations in the western part of the Washakie and Great Divide Basins, the Allen Ridge Formation and Pine Ridge Sandstone in the eastern part of the Washakie and Great Divide Basins, and the Iles and lower part of the Williams Fork Formations in the Sand Wash Basin (figs. 2–4).

Production from the Rock Springs–Ericson Assessment Unit to date has been minimal. Of the 83 wells listed as Ericson producers in the Petroleum Information production file (IHS Energy Group, 2001) only 18 are perforated exclusively in the Ericson. The remaining 65 wells are perforated in both the Almond and the Ericson. Of the 47 wells listed as Rock Springs producers, 36 are also perforated in the Almond. Production from Rock Springs and Ericson wells that are co-completed in the Almond was assigned to the Almond Continuous Gas Assessment Unit. Thus, only 29 wells were identified as exclusively Rock Springs–Ericson producers. There have been few attempts in the past 12 years to complete Ericson wells, largely because of water problems encountered earlier. Only 10 of the 83 Ericson producers were completed in 1990 or later; 10 of the Rock Springs wells were also completed in 1990 or later. Law (2002) summarized water problems in blanketlike reservoir sandstone in Rocky Mountain basin-centered gas systems including the Ericson. Ericson perforations

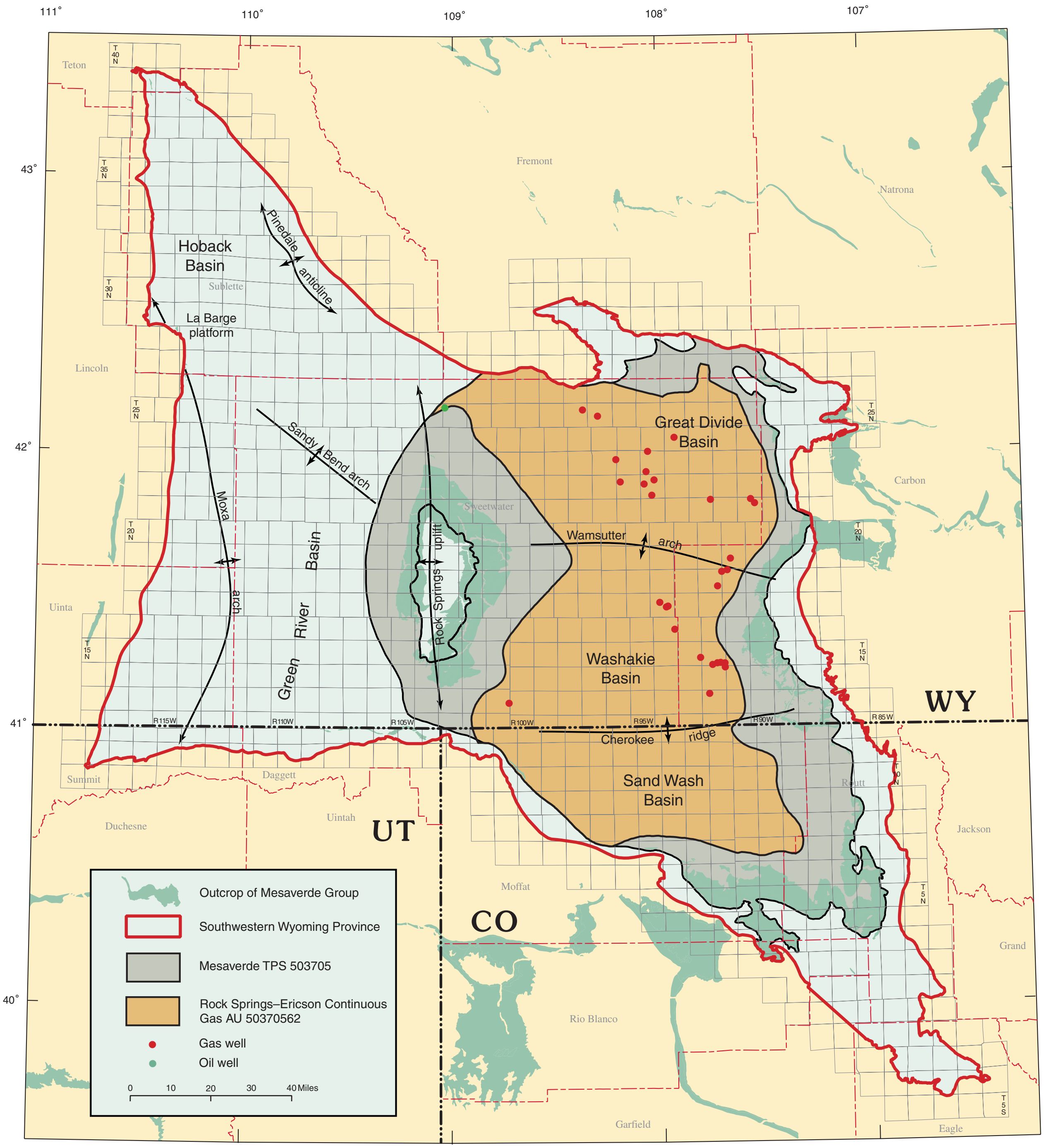


**Figure 16.** Extent of the Rock Springs–Ericson continuous gas assessment unit (AU 50370562) in the Mesaverde Total Petroleum System, Southwestern Wyoming Province. The assessment unit is defined as that area where thermal maturities exceed a vitrinite reflectance of 0.8 percent at the base of the Rock Springs Formation.

in these pre-1990s wells were commonly sealed off once water problems in the Ericson were recognized.

Water problems may also be encountered in the blanket-like marginal marine sandstones in the Rock Springs Formation, although there are presently too few completions to demonstrate this. Water problems have occurred in marginal marine blanketlike reservoirs in other Rocky Mountain basins including the Rollins and Trout Creek Sandstone Members of the Mesaverde Formation in the Piceance Basin in western Colorado (Johnson and others, 1987) and marginal marine sandstones in the lower part of the Mesaverde Formation in the Wind River Basin, in central Wyoming, north of the Southwestern Wyoming Province (Johnson and others, 1996).

Figure 17 shows the EUR distribution for the 27 of the 29 Rock Springs–Ericson producers for which production information is available. The median EUR for these wells is only 0.12 BCF. Figure 18 shows EURs by thirds, but data are too sparse to draw any meaningful conclusions. These EURs are not considered to represent future production from the Rock Springs–Ericson as most of the completions are old and did not incorporate recent advances in drilling and completion technologies. Because of the lack of information and because the two assessment units are similar geologically, the Mesaverde Continuous Oil and Gas Assessment Unit in the Piceance Basin (AU 50200263) was used as an analog to estimate total recovery for untested cells having potential for additions to reserves over the next 30 years. Both assessment units produce largely from lenticular sandstones interbedded with coals and carbonaceous shales deposited in similar depositional settings.

The estimated minimum, median, and maximum area of the Rock Springs–Ericson Assessment Unit that is untested are 98.7, 99.4, and 99.9 percent, respectively (Appendix B). Although most of the Almond tests in the Southwestern Wyoming Province bottomed in the uppermost Ericson, these are not considered tests of the Ericson, as the top of the Ericson was used only as a convenient stratigraphic marker to let the driller know that the entire Almond section had been penetrated. Only those wells that penetrated a significant portion of the Ericson and older strata are considered legitimate tests.

The estimated minimum, median, and maximum percentages of untested assessment-unit area that has potential for additions to reserves in the next 30 years is 28, 48, and 72 percent, respectively (Appendix B). A necessary condition is that the total recovery per cell is greater than or equal to the minimum recovery per cell of 0.02 BCFG, and it is likely that this minimum amount of gas can be recovered from a majority of the untested cells in the assessment unit. The assessment unit, though largely untested, everywhere contains thick sequences of reservoir rocks that were deposited in depositional settings similar to successfully developed, basin-centered accumulations throughout the Rocky Mountains. Most of the tests of this assessment unit date to the 1970s and 1980s when our understanding of how to produce the tight reservoirs in basin-centered accumulation was in its infancy. Testing of this assessment unit largely ceased once the productive potential of the marginal marine bar sandstones in the Almond was appreciated.

The minimum, median, and maximum total recovery for untested cells having potential for additions to reserves in the next 30 years are 0.02, 0.4, and 3.0 BCFG, respectively (Appendix B). These estimates assume that future production for the Rock Springs–Ericson Assessment Unit would be significantly greater than production from the assessment unit thus far because most completions are more than 12 years old, and drilling and completion practices have improved significantly since these wells were completed. An analog for the lenticular sandstone reservoirs in the Rock Springs Formation is the productive lenticular sandstones in the lower part of the Williams Fork Formation in the Piceance Basin Continuous Gas Assessment Unit (Johnson and Roberts, 2003). Lenticular sandstones in both assessment units were deposited in coastal plain and fluvial settings. These sandstones in the Piceance Basin are currently being developed using spacing of as little as 20 acres. An analog for the marginal marine sandstones in the Rock Springs is the production from similar bar sandstones in the overlying Almond Formation. The large number of currently producing Almond wells within the boundaries of the Rock Springs-Ericson Assessment Unit may help spur development, as these wells could be deepened to test the Rock Springs Formation and Ericson Sandstone for a fraction of the cost of a new well. Mean estimate of potential for additions to reserves over the next 30 years is 12.18 TCF (table 1).

## Mesaverde Coalbed Gas Assessment Unit (AU 50370581)

The Mesaverde Coalbed Gas Assessment Unit (50370581) is defined as that area where significant coal occurs in the Mesaverde TPS at depths of 6,000 ft and less (fig. 19). The assessment unit is divided into two areas: the first is around the margins of the Rock Springs uplift and the second is along the east margins of the Great Divide and Washakie Basins and the east and south margins of the Sand Wash Basin (fig. 19). The Mesaverde Coalbed Gas Assessment Unit covers about 3 million acres of the Mesaverde TPS. A 6,000-ft maximum depth was used to define the eastern, southern, and northern boundaries of the Mesaverde Coalbed Gas Assessment Unit (50370581), while the western limit is defined by a combination of the 6,000-ft maximum depth cutoff and the western pinch-out of the Lewis Shale (fig. 20). The stratigraphically highest coals in the Mesaverde Group are in the Almond Formation, and the depth to the top of the Almond was used to define the 6,000-ft cutoff. Using this criterion means that coals in units below the Almond are at depths greater than 6,000 ft in the deeper portions of the assessment unit. Significant coal occurs in the Mesaverde Group throughout all but the northeast corner of the Mesaverde TPS, but unusually thick accumulations are in the Rock Springs Formation northeast of the Rock Springs uplift (Tyler and others, 1995, their fig. 29) and in the Williams Fork

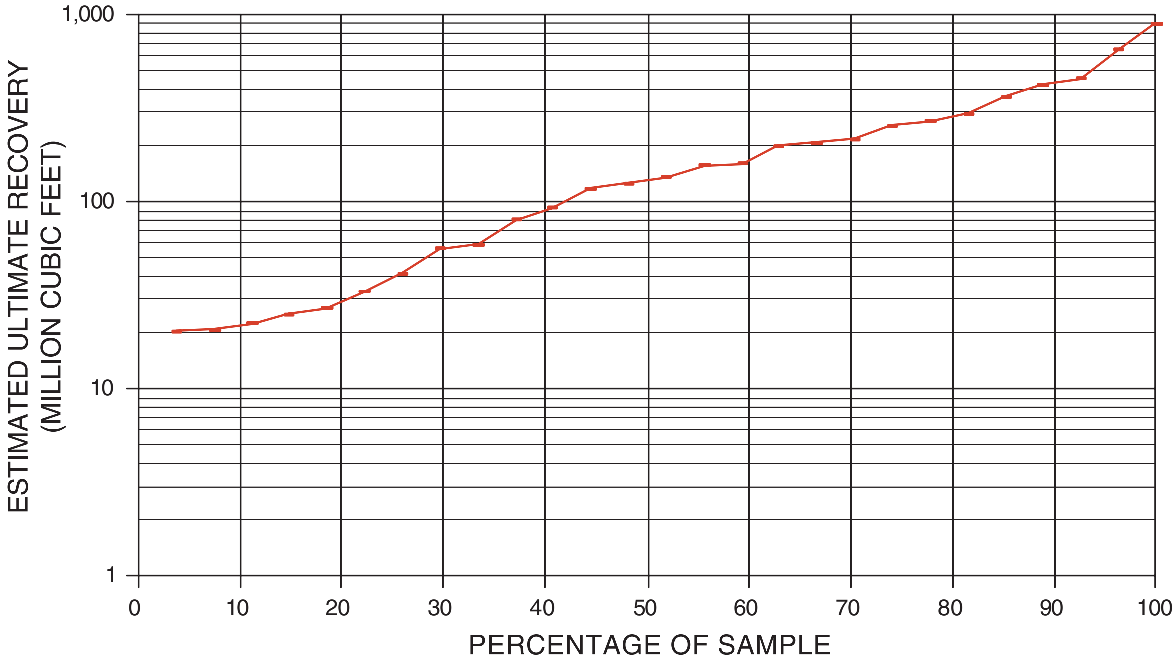


**Figure 17.** Distribution of Estimated Ultimate Recoveries (EURs) for gas wells within the Rock Springs–Ericson Continuous Gas Assessment Unit (AU 50370562), Mesaverde Total Petroleum System, Southwestern Wyoming Province. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown.

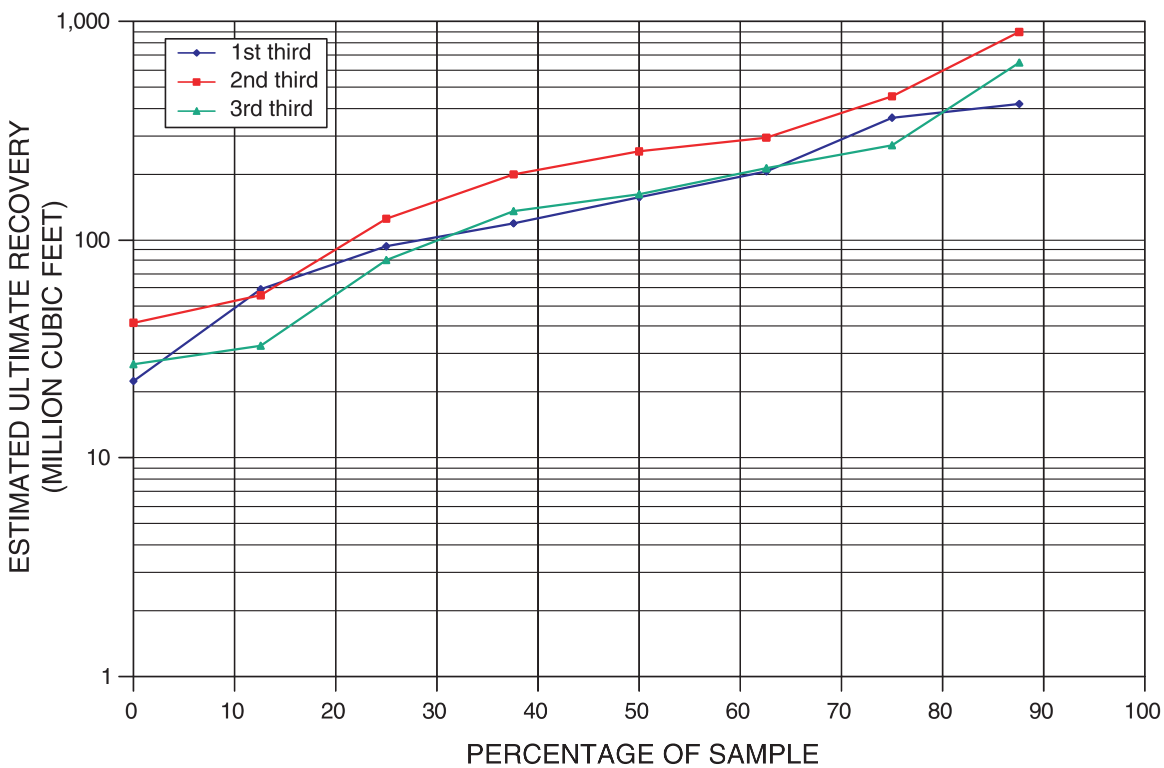


**Figure 18.** Distribution of Estimated Ultimate Recoveries (EURs) by thirds for gas wells within the Rock Springs–Ericson Continuous Gas Assessment Unit (AU 50370562), Mesaverde Total Petroleum System, Southwestern Wyoming Province. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas (BCFG) are shown.

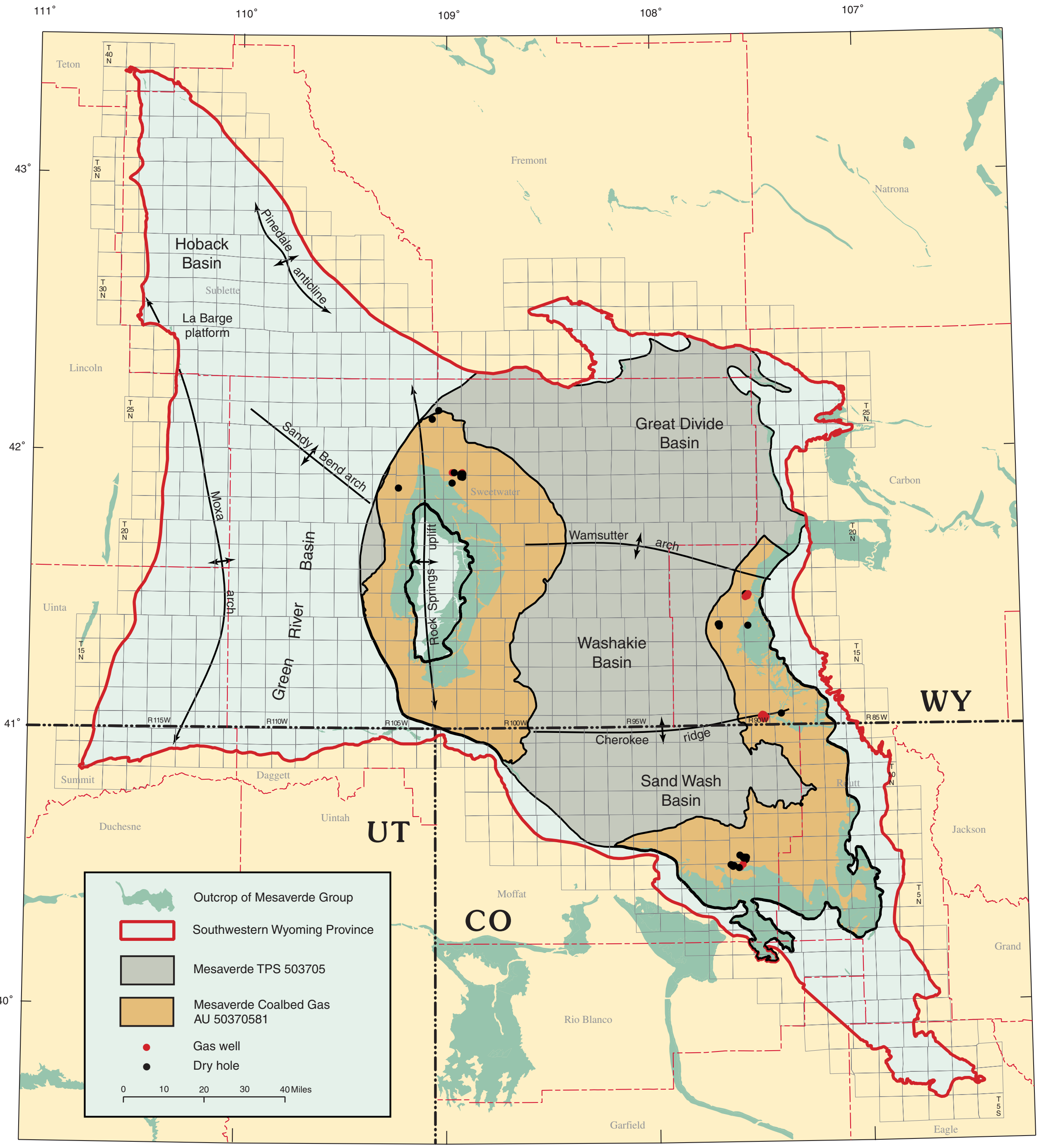


**Figure 19.** Extent of the Mesaverde Coalbed Gas Assessment Unit in the Mesaverde Total Petroleum System, Southwestern Wyoming Province. The boundary is defined as that area where the top of the Almond Formation, the stratigraphically highest unit in the assessment unit, is at a depth of 6,000 feet or less.

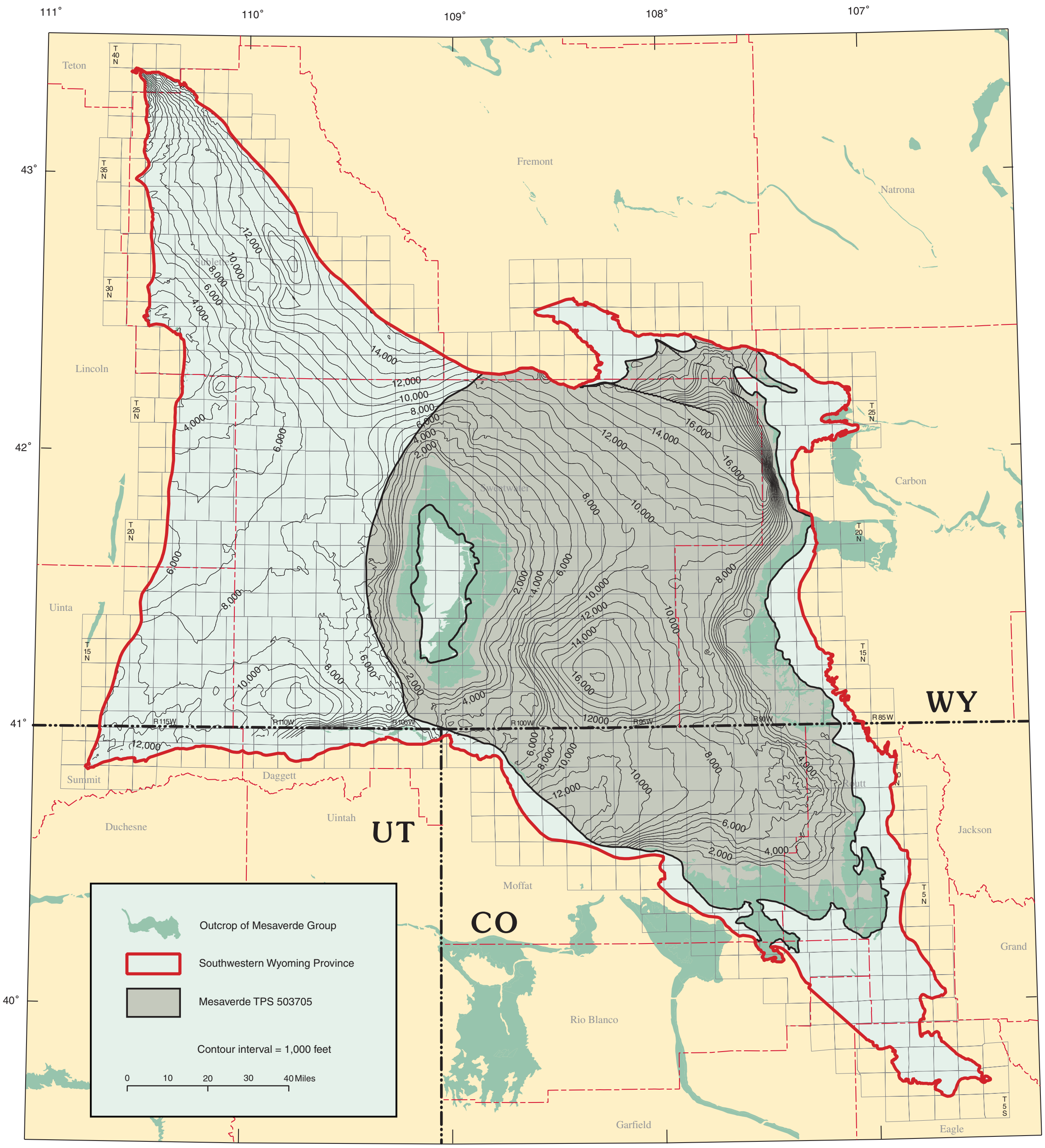


**Figure 20.** Approximate depth to the top of the Mesaverde Group, in the Mesaverde Total Petroleum System, Southwestern Wyoming Province. Contour interval is 1,000 feet.

Formation in the Sand Wash Basin (Tyler and others, 1995, their fig. 33). Coals in this assessment unit contain as much as 540 standard cubic feet per ton (Tyler and others, 1995). Little gas is present in the coals at depths of less than 1,000 ft (Tyler and others, 1995, their fig. 57); thus, it is unlikely that a shallow coalbed methane play similar to that currently being developed in the Powder River Basin will develop here.

In the early 1990s, wells were drilled for coalbed methane 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 (fig. 20), 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 (2004) several active projects in the TPS. These recent wells are currently undergoing dewatering, and gas flows have not as yet peaked.

The estimated minimum, median, and maximum percentage of untested assessment-unit area that has potential for additions to reserves in the next 30 years are 1, 10, and 20 percent, respectively (Appendix C). The Mesaverde Group Coalbed Methane Assessment Unit in the Uinta and Piceance Basins of Utah and Colorado (Johnson and Roberts, 2003) is used here as an analog. Coals in both assessment units were deposited in similar lower coastal-plain depositional settings. Attempts to develop coalbed methane in the Uinta and Piceance assessment unit have been plagued by water problems near areas of major recharge, low coal permeabilities, and undersaturated coal (Reinecke and others, 1991; Johnson and others, 1996). The estimated minimum percentage of untested assessment-unit area that has potential for additions to reserves in the next 30 years assumes that the excessive amounts of water that have hindered work in this assessment unit in the past will be found to be pervasive throughout almost all of the unit. The median estimate 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 estimate 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.

The minimum, median, and maximum estimates of total recovery per cell are 0.02, 0.06 and 2.0 BCFG, respectively (Appendix C). These values are somewhat lower than those estimated for the analog Mesaverde Group Coalbed Methane Assessment Unit in the Piceance and Uinta Basins (minimum: 0.02 BCFG, median: 0.08 BCFG, maximum: 5 BCFG) largely because efforts to develop the coalbed methane in the Uinta-Piceance assessment unit have met with more success than those thus far in the Mesaverde TPS of the Southwestern Wyoming Province. Mean estimate of gas that has potential for additions to reserves over the next 30 years is 249 BCFG (table 1).

## Mesaverde Conventional Oil and Gas Assessment Unit (AU 50370501)

The Mesaverde Conventional Oil and Gas Assessment Unit (AU 50370501) encompasses that part of the Mesaverde TPS where thermal maturities at the top of the Mesaverde TPS (top of Almond Formation) are $R_o$ 0.8 percent or less (fig. 21). The assessment unit overlaps with the Rock Springs–Ericson Assessment Unit (AU 50370562), and each field within the overlap area was examined and placed into one of the assessment units depending on production characteristics. This assessment unit contains 2 oil and 12 gas fields exceeding the minimum size of 0.5 million barrels of oil grown (estimate of ultimate recovery from field) (Appendix C). Both oil fields, Patrick Draw and Desert Springs, were discovered in 1959; thus, there has not been an oil field of the minimum size discovered in over 40 years. The most recent gas field discovered that exceeds the minimum field size of 3 BCF was Blue Sky field in 1996. Prior to this, the last gas field discovered was Tenmile Draw field in 1972.

The estimated minimum, median, and maximum number of undiscovered oil and gas fields are, respectively, 1, 2, and 3 for oil fields and 2, 5, and 12 for gas fields (Appendix D), while the estimated minimum, median, and maximum size of undiscovered oil and gas accumulations are 0.5, 1.0, and 5.0 MMBO for oil fields and 3, 6, and 30 BCFG for gas fields. Mean estimate of undiscovered oil is 2.3 MMBO, and the mean estimate of undiscovered gas is 55.7 BCF (table 1).

# Summary of Results

Tabulated results of undiscovered oil, gas, and gas liquids in the Mesaverde Total Petroleum System that have the potential for additions to reserves are listed in table 1. The mean estimate of the total oil is 2.30 MMBO, mean total gas is 25.83 TCF, and the mean estimate of total gas liquids is 347.40 MMBNGL. For gas, 13.35 TCF is in the Almond Continuous Gas Assessment Unit, 12.18 TCF is in the Rock Springs–Ericson Continuous Gas Assessment Unit, and 248.70 BCF is in the Mesaverde Coalbed Gas Assessment Unit. All of the undiscovered oil is in the Mesaverde Conventional Oil and Gas Assessment Unit.

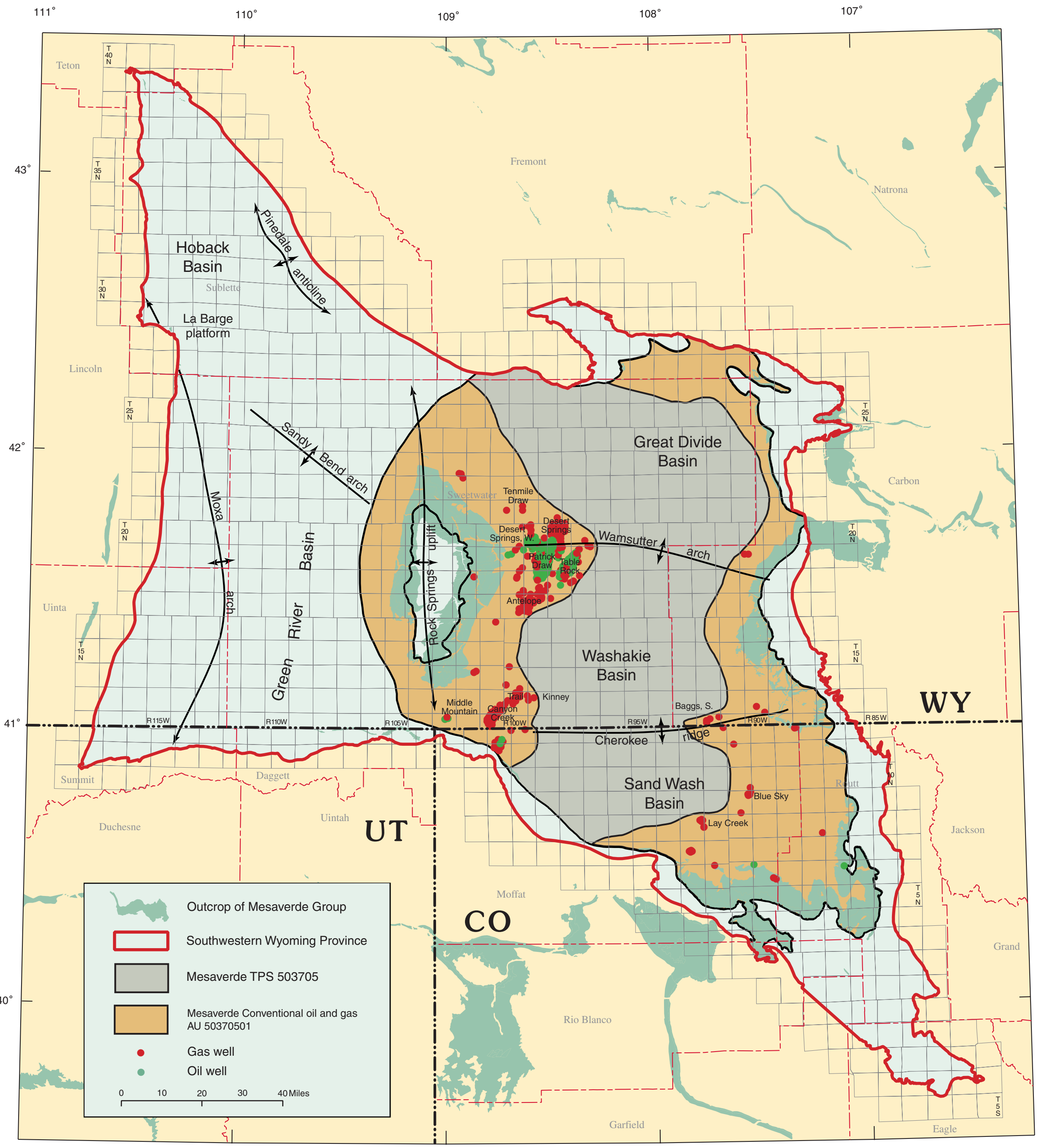


**Figure 21.** Mesaverde Conventional Oil and Gas Assessment Unit (AU 50370501) in the Mesaverde Total Petroleum System, Southwestern Wyoming Province. The Assessment Unit is defined as that area where thermal maturities are less than a vitrinite reflectance of 0.8 percent at the top of the total petroleum system.

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**Appendix A.** Input parameters for the Almond Continuous Gas Assessment Unit (AU 50370561), Mesaverde 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: | 8/21/2002 |
| Region:…………………… | North America | Number: | 5 |
| Province:…………………. | Southwestern Wyoming | Number: | 5037 |
| Total Petroleum System:. | Mesaverde | Number: | 503705 |
| Assessment Unit:………. | Almond Continuous Gas | Number: | 50370561 |
| Based on Data as of:…… | IHS Energy Group, 2001, Wyoming Oil and Gas Conservation Commission, WGA Guidebooks | | |
| 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:………… 1,790
Number of tested cells with total recovery per cell ≥ minimum: ……... 1,086
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 3rd discovered 0.7 2nd 3rd 1.1 3rd 3rd 0.7

**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 3,018,000 median 3,353,000 maximum 3,688,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres): (values are inherently variable)
calculated mean 177 minimum 40 median 160 maximum 449

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 88 median 91 maximum 93

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 35 median 52 maximum 76

**Appendix A.** Input parameters for the Almond Continuous Gas Assessment Unit (AU 50370561), Mesaverde Total Petroleum System, Southwestern Wyoming Province.—Continued

Assessment Unit (name, no.)
Almond Continuous Gas, Assessment Unit 50370561

### 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)
(mmbo for oil A.U.; bcfg for gas A.U.) minimum 0.02 median 0.9 maximum 20

### 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)….………….…… | 5 | 15 | 25 |

### 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 | 1.90 | 6.10 |
| $CO_2$ content (%)……………………………..….. | 0.10 | 2.30 | 5.70 |
| Hydrogen-sulfide content (%)……………...…….. | 0.00 | 0.00 | 0.00 |
| Drilling depth (m)…………………………………. | 2,300 | 3,350 | 5,800 |
| Depth (m) of water (if applicable)………………. | | | |

| Success ratios: | calculated mean | minimum | median | maximum |
|---|---|---|---|---|
| Future success ratio (%)… | 81 | 70 | 80 | 95 |

Historic success ratio, tested cells (%) 61

**Appendix B.** Input parameters for the Rock Springs–Ericson Continuous Gas Assessment Unit (AU 50370562), Mesaverde 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: | 8/21/2002 |
| Region:…………………… | North America | Number: | 5 |
| Province:………………… | Southwestern Wyoming | Number: | 5037 |
| Total Petroleum System:. | Mesaverde | Number: | 503705 |
| Assessment Unit:………. | Rock Springs-Ericson Continuous Gas | Number: | 50370562 |
| Based on Data as of:…… | IHS Energy Group, 2001, Wyoming Oil and Gas Conservation Commission | | |
| Notes from Assessor….. | Analogs: Piceance Basin Continuous Gas and Piceance Basin Transitional Gas Assessment Units | | |

### 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:………… 290
Number of tested cells with total recovery per cell > minimum: ……... 97
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 3rd discovered 0.15 2nd 3rd 0.25 3rd 3rd 0.15

**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 3,925,000 median 4,361,000 maximum 4,797,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres): (values are inherently variable)
calculated mean 85 minimum 20 median 80 maximum 180

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 98.7 median 99.4 maximum 99.9

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 28 median 48 maximum 72

**Appendix B.** Input parameters for the Rock Springs–Ericson Continuous Gas Assessment Unit (AU 50370562), Mesaverde Total Petroleum System, Southwestern Wyoming Province.—Continued

Assessment Unit (name, no.)
Rock Springs-Ericson Continuous Gas, Assessment Unit 50370562

**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 | 0.4 | 3 |

**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)….…………..…… | 6 | 12 | 18 |

**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 | 1.90 | 6.10 |
| $CO_2$ content (%)……………………………..….. | 0.10 | 2.30 | 5.70 |
| Hydrogen-sulfide content (%)……………...……. | 0.00 | 0.00 | 0.00 |
| Drilling depth (m)…………………………………. | 2,300 | 3,050 | 5,900 |
| Depth (m) of water (if applicable)………………. | | | |

| Success ratios: | calculated mean | minimum | median | maximum |
|---|---|---|---|---|
| Future success ratio (%).. | 85 | 80 | 85 | 90 |

Historic success ratio, tested cells (%) 33

**Appendix C.** Input parameters for the Mesaverde Coalbed Gas Assessment Unit (AU 50370581), Mesaverde 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 | Number: | 503705 |
| Assessment Unit:………. | Mesaverde Coalbed Gas | Number: | 50370581 |
| Based on Data as of:…… | IHS Energy Group, 2001, Wyoming Oil and Gas Conservation Commission | | |
| Notes from Assessor….. | Analog: Mesaverde Group Coalbed Gas of the Uinta-Piceance Basin | | |

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### 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:………… 50

Number of tested cells with total recovery per cell ≥ minimum: ……... 1

Established (>24 cells ≥ min.) ______ Frontier (1-24 cells) X Hypothetical (no cells) ______

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

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

**Assessment-Unit Probabilities:**

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

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

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 2,836,000 median 2,985,000 maximum 3,134,000

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 99.7 median 99.8 maximum 99.9

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 for the Mesaverde Coalbed Gas Assessment Unit (AU 50370581), Mesaverde Total Petroleum System, Southwestern Wyoming Province.—Continued

Assessment Unit (name, no.)
Mesaverde Coalbed Gas, Assessment Unit 50370581

**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)
(mmbo for oil A.U.; bcfg for gas A.U.) minimum 0.02 median 0.06 maximum 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 (%)……………………….....….. | 0.10 | 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 |

Historical success ratio, tested cells (%) ________

**Appendix D.** Input parameters for the Mesaverde Conventional Gas Assessment Unit (AU 50370501), Mesaverde 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 | Number: | 503705 |
| Assessment Unit:……. | Mesaverde Conventional Oil and Gas | Number: | 50370501 |
| 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 ove 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: 2 Gas: 12
Established (>13 accums X Frontier (1-13 accums.) Hypothetical (no accums.)

Median size (grown) of discovered oil accumulation (mmbo):
1st 3rd 2nd 3rd 3rd 3rd
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd 170 2nd 3rd 8.4 3rd 3rd

**Assessment-Unit Probabilities:**

| Attribute | Probability of occurrence (0-1.0) |
|---|---|
| 1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. ≥ minimum size……………… | 1.0 |
| 2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. ≥ minimum size…… | 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. (> | median no. | max no. |
|---|---|---|---|
| Oil Accumulations:………………… | 1 | 2 | 3 |
| Gas Accumulations:………………. | 2 | 5 | 12 |

**Sizes of Undiscovered Accumulations:** What are the sizes (**grown**) of the above accums?:
(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 | 6 | 30 |

**Appendix D.** Input parameters for the Mesaverde Conventional Gas Assessment Unit (AU 50370501), Mesaverde Total Petroleum System, Southwestern Wyoming Province.—Continued.

Assessment Unit (name, no.)
Mesaverde Conventional Oil and Gas, Assessment Unit 50370501

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

| Oil Accumulations: | minimum | median | maximum |
|---|---|---|---|
| Gas/oil ratio (cfg/bo) | 4,120 | 8,239 | 12,359 |
| NGL/gas ratio (bngl/mmcfg) | 18.5 | 37 | 55.5 |
| **Gas Accumulations:** | **minimum** | **median** | **maximum** |
| Liquids/gas ratio (bliq/mmcfg) | 5.92 | 11.85 | 17.77 |
| 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) | 42 | 43 | 44 |
| Sulfur content of oil (%) | 0 | 0 | 0 |
| Drilling Depth (m) | 881 | 1,200 | 1,544 |
| Depth (m) of water (if applicable) | | | |
| **Gas Accumulations:** | **minimum** | **median** | **maximum** |
| Inert gas content (%) | 0.1 | 0.7 | 2.5 |
| $CO_2$ content (%) | 0.1 | 1.29 | 2.3 |
| Hydrogen-sulfide content (%) | 0 | 0 | 0 |
| Drilling Depth (m) | 1,320 | 1,670 | 2,028 |
| Depth (m) of water (if applicable) | | | |

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