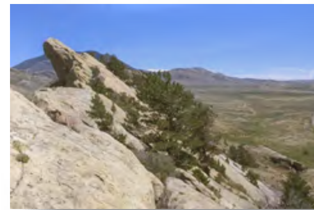
Chapter 11

Geologic Assessment of Undiscovered Petroleum Resources in the Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming and Colorado



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By Stephen B. Roberts

Chapter 11 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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Abstract

The Lance–Fort Union Composite Total Petroleum System (CTPS) in the Southwestern Wyoming Province is a genetically related system of source rocks and hydrocarbon accumulations contained within Upper Cretaceous and lower Tertiary strata. The CTPS includes the Fox Hills Sandstone and overlying Lance Formation (Upper Cretaceous: Maastrichtian), and lower Tertiary rocks in the Fort Union Formation (Paleocene), and in the Wasatch (part) and Battle Spring Formations (Eocene). The petroleum system encompasses about 6,112,000 acres (9,550 square miles) in Wyoming and Colorado and includes the Great Divide, Washakie, and Sand Wash structural basins and intervening Wamsutter arch and Cherokee ridge. The stratigraphic base of the petroleum system is placed at the contact between the Fox Hills Sandstone and the underlying Lewis Shale; this contact is intertonguing and conformable. Definition of the stratigraphic top of the CTPS is somewhat problematic because of intertonguing of the Wasatch and Green River Formations. In general, where lacustrine shale units in the Green River Formation are present, the top of the petroleum system is placed at the base of the lowest, pervasive lacustrine shale unit in the Green River Formation. This horizon generally corresponds to the top of the main body of the Wasatch Formation, or the top of age equivalent units in the Hiawatha Member of the Wasatch Formation near the Rock Springs uplift, and in the Red Desert Tongue of the Wasatch Formation in the central part of the Great Divide Basin. Where lacustrine shale units in the Green River Formation are not present, the top of the CTPS is placed at the top of the undifferentiated Wasatch Formation or at the top of age equivalent units in the Battle Spring Formation.

Coal beds and associated noncoal, carbonaceous strata within the Lance and Fort Union Formations are considered to be the primary source rocks for hydrocarbon generation within the Lance–Fort Union CTPS; these source rocks are composed of humic, Type-III organic matter, and thus, are considered to be gas prone. Source rocks in the basal part of the Lance Formation have reported thermal maturity (R_o) values ranging from less than 0.50 percent to more than 1.60 percent, based on direct measurements of vitrinite reflectance from Lance coal and carbonaceous shale beds, or extrapolated from vitrinite reflectance values for the top of the Lewis Shale. Measured R_o values for coal and carbonaceous source rocks near the base of the Fort Union Formation range from less than 0.50 percent to about 1.53 percent. Within the CTPS, the highest reported R_o values for the Lance and Fort Union Formations were measured at depths from about 12,000 to 13,000 feet in the deep, south-central part of the Washakie Basin.

Primary reservoirs in the Lance–Fort Union CTPS are fluvial sandstone deposits in the Lance, Fort Union, and Wasatch Formations, with additional reservoirs in marginal marine (shoreface) sandstone in the Fox Hills Sandstone. Gas generated from deeply buried coal and carbonaceous strata migrated relatively short distances into low-permeability (tight) sandstone reservoirs in close proximity to mature source rocks. Hydrocarbons in the CTPS also migrated vertically and laterally (updip) into shallow (less than 8,000 feet) reservoirs in conventional accumulations along basin margins or on intervening structural arches. Because of the generally discontinuous nature of fluvial sandstone units and the presence of thick, relatively impermeable mudstone and siltstone successions within the Lance, Fort Union, and Wasatch Formations, faults or fracture systems may have been critical for successful hydrocarbon migration from source rocks at depth into shallow conventional reservoirs. Coal beds in the Lance and Fort Union Formations also serve both as source rocks and as reservoirs for potential coalbed-gas accumulations.

The Lance–Fort Union CTPS contains undiscovered gas resources in continuous accumulations (basin-centered gas and coalbed-gas resources) and gas and oil resources in shallow conventional accumulations. Within the CTPS, four assessment units have been defined: the Lance–Fort Union Continuous Gas Assessment Unit, the Lance Coalbed Gas Assessment Unit, the Fort Union Coalbed Gas Assessment Unit, and the Lance–Fort Union Conventional Oil and Gas Assessment Unit. The mean estimate of total undiscovered gas resources in the Lance–Fort Union Composite Total Petroleum System

is about 8.9 trillion cubic feet (TCF). Of this total, a mean of about 7.6 TCF is included in the Lance–Fort Union Continuous Gas Assessment Unit, a mean of 0.17 TCF is estimated for the Lance Coalbed Gas Assessment Unit, and a mean of about 0.94 TCF is estimated for the Fort Union Coalbed Gas Assessment Unit. An additional mean estimate of about 0.25 TCF of undiscovered gas is included in the Lance–Fort Union Conventional Oil and Gas Assessment Unit. Undiscovered natural gas resources in the Lance–Fort Union CTPS represent about 10 percent of the mean estimated total of 84.6 TCF of gas in the Southwestern Wyoming Province.

Introduction

The Lance–Fort Union Composite Total Petroleum System (CTPS) in the Southwestern Wyoming Province is a genetically related system of source rocks and hydrocarbon accumulations contained within Upper Cretaceous and lower Tertiary strata (fig. 1). Assignment of stratigraphic units to Lance–Fort Union CTPS is based on the presence of thermally mature source rocks (primarily coal and carbonaceous strata) within the Lance and Fort Union Formations (for example, see Law and others, 1989; Law, 1996) and the presence of sandstone reservoirs that contain or have the potential to trap hydrocarbons that have migrated from these source rocks. Considering these criteria, the CTPS includes strata within the Upper Cretaceous (Maastrichtian) Fox Hills Sandstone and Lance Formation, and lower Tertiary rocks in the Fort Union Formation (Paleocene), and in the Wasatch (part) and Battle Spring Formations (Eocene).

The petroleum system encompasses about 6,112,000 acres (9,550 mi^2) in Wyoming and Colorado (fig. 2) and includes the Great Divide, Washakie, and Sand Wash structural basins and intervening Wamsutter arch and Cherokee ridge (fig. 3). The eastern and southeastern boundary of the CTPS is defined by the outcrop limits of the Lance Formation. The western and southwestern boundary (part) of the petroleum system is coincident with the depositional limit of the Lewis Shale (Hettinger and Roberts, Chapter 9, this CD–ROM); the western boundary is also a common boundary with the Mesaverde–Lance–Fort Union Composite Total Petroleum System in the western part of the province (Finn and others, Chapter 10, this volume). In some areas surrounding the Rock Springs uplift and in other areas where the Lance Formation is truncated or absent, the CTPS boundary is defined by the mapped or projected limit of the Fort Union Formation.

The base of the petroleum system is placed at the contact between the Fox Hills Sandstone and the underlying Lewis Shale; this contact is intertonguing and conformable. The stratigraphic interval from the Lewis Shale upward through the Fox Hills and the Lance Formation (fig. 1) generally represents a transition from offshore marine environments (Lewis Shale) and shoreface or marginal-marine environments (Fox Hills Sandstone) to a coastal-plain and fluvial/alluvial depositional setting (Lance Formation) as the Western Interior Seaway retreated from the region during the latest Cretaceous (for example, see Roberts and Kirschbaum, 1995). In this study, the Fox Hills Sandstone is generally considered as the uppermost regressive, shoreface sandstone succession deposited during final retreat of the seaway. However, in certain areas of the CTPS, such as the northern part of the Great Divide Basin, complex stacking and intertonguing of offshore, shoreface, and coal-bearing coastal plain deposits through several hundred feet or more of strata (for example, see Hettinger and Roberts, Chapter 9, this volume) complicates the identification of a unique Fox Hills Sandstone. In cases such as this, the base of the petroleum system is placed at the base of the lowermost shoreface sandstone that is underlain by marine shale and overlain by coal-bearing coastal-plain deposits. Estimated depth to the base of the Fox Hills Sandstone (base of the petroleum system) is shown in figure 4.

Definition of the stratigraphic top of the CTPS is somewhat problematic because of intertonguing of the Wasatch and Green River Formations. In general, where lacustrine shale units in the Green River Formation are present, the top of the Lance–Fort Union CTPS is placed at the base of the lowest, pervasive lacustrine shale unit. This horizon generally corresponds to the top of the main body of the Wasatch Formation, or the top of age equivalent units (in part) in the Hiawatha Member of the Wasatch Formation near the Rock Springs uplift (Nightingale, 1938) and in the Red Desert Tongue of the Wasatch Formation in the central part of the Great Divide Basin (Pipiringos, 1961). Where lacustrine shale units in the Green River Formation are not present, the top of the CTPS is placed at the top of the undifferentiated Wasatch Formation or at the top of age-equivalent units in the Battle Spring Formation. Inclusion of Wasatch Formation units within the Lance–Fort Union CTPS relates primarily to the potential for fluvial sandstone beds within these strata to trap migrated hydrocarbons generated by Lance and(or) Fort Union Formation source rocks. It should be noted that a potential for coalbed-gas resources within certain of these same units (for example, the main body and Red Desert Tongue of the Wasatch Formation) also exists. However, because of the close genetic relation between coal beds in the Wasatch Formation and lacustrine shale in the Green River Formation (for example, see Pipiringos, 1961; Masursky, 1962; Roehler, 1987a), hypothetical coalbed gas resources in the Wasatch Formation are assessed as part of the overlying Wasatch–Green River CTPS (Roberts, Chapter 12, this volume).

The Lance–Fort Union CTPS contains undiscovered gas resources in continuous accumulations, including potential basin-centered gas and coalbed-gas resources, and gas and oil resources in shallow conventional accumulations. Within the CTPS four assessment units have been defined: the Lance–Fort Union Continuous Gas Assessment Unit, the Lance Coalbed Gas Assessment Unit, the Fort Union Coalbed Gas Assessment Unit, and the Lance–Fort Union Conventional Oil and Gas Assessment Unit. Because oil resources are minor with respect to gas, undiscovered oil resources were not

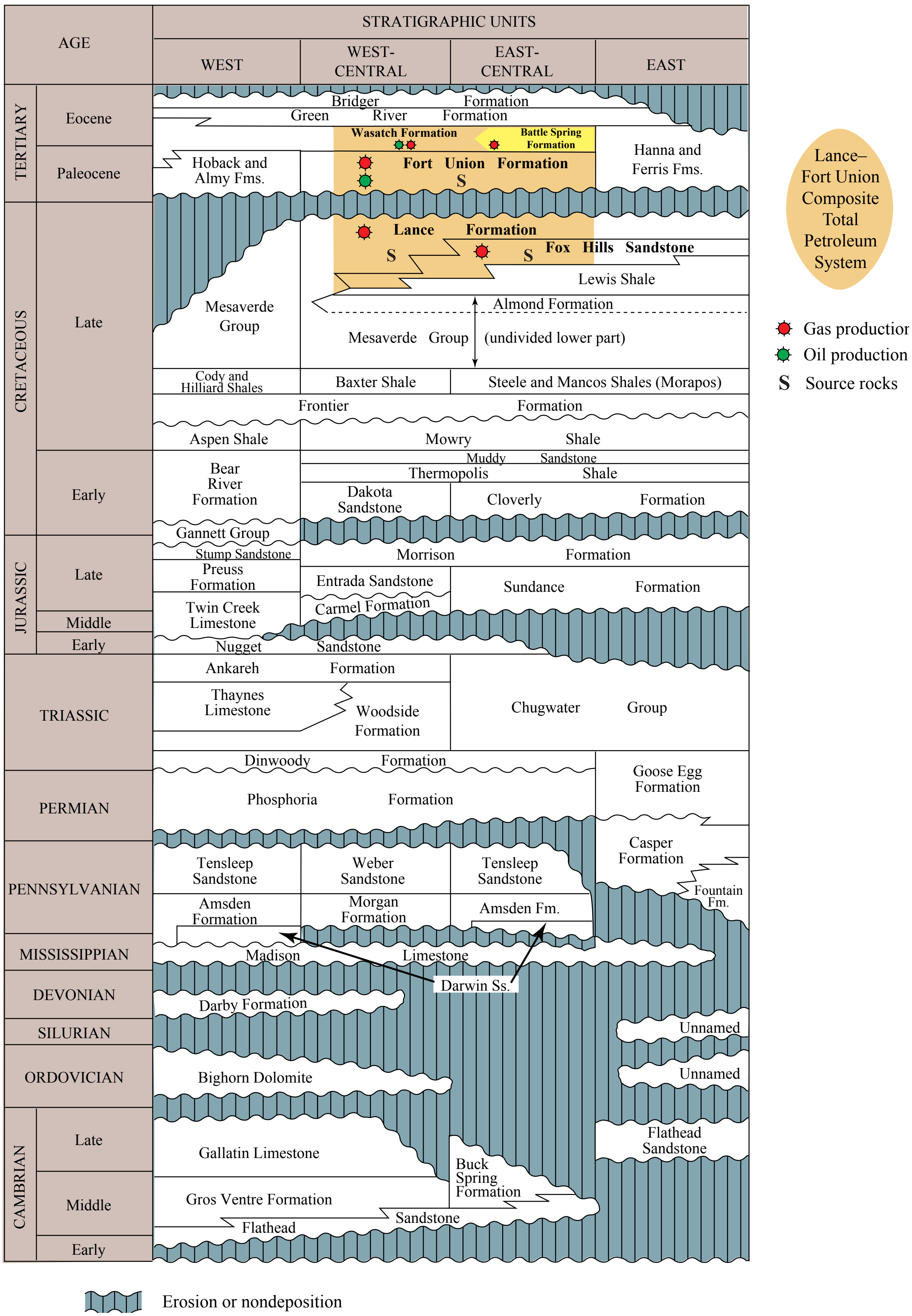

Figure 1. Generalized stratigraphic chart for the Southwestern Wyoming Province in Wyoming, Colorado, and Utah, showing units in the Lance–Fort Union Composite Total Petroleum System, and intervals of hydrocarbon production and source rocks. Wasatch Formation includes age equivalent units in the Battle Spring Formation in the Great Divide Basin. Modified from Law (1996).

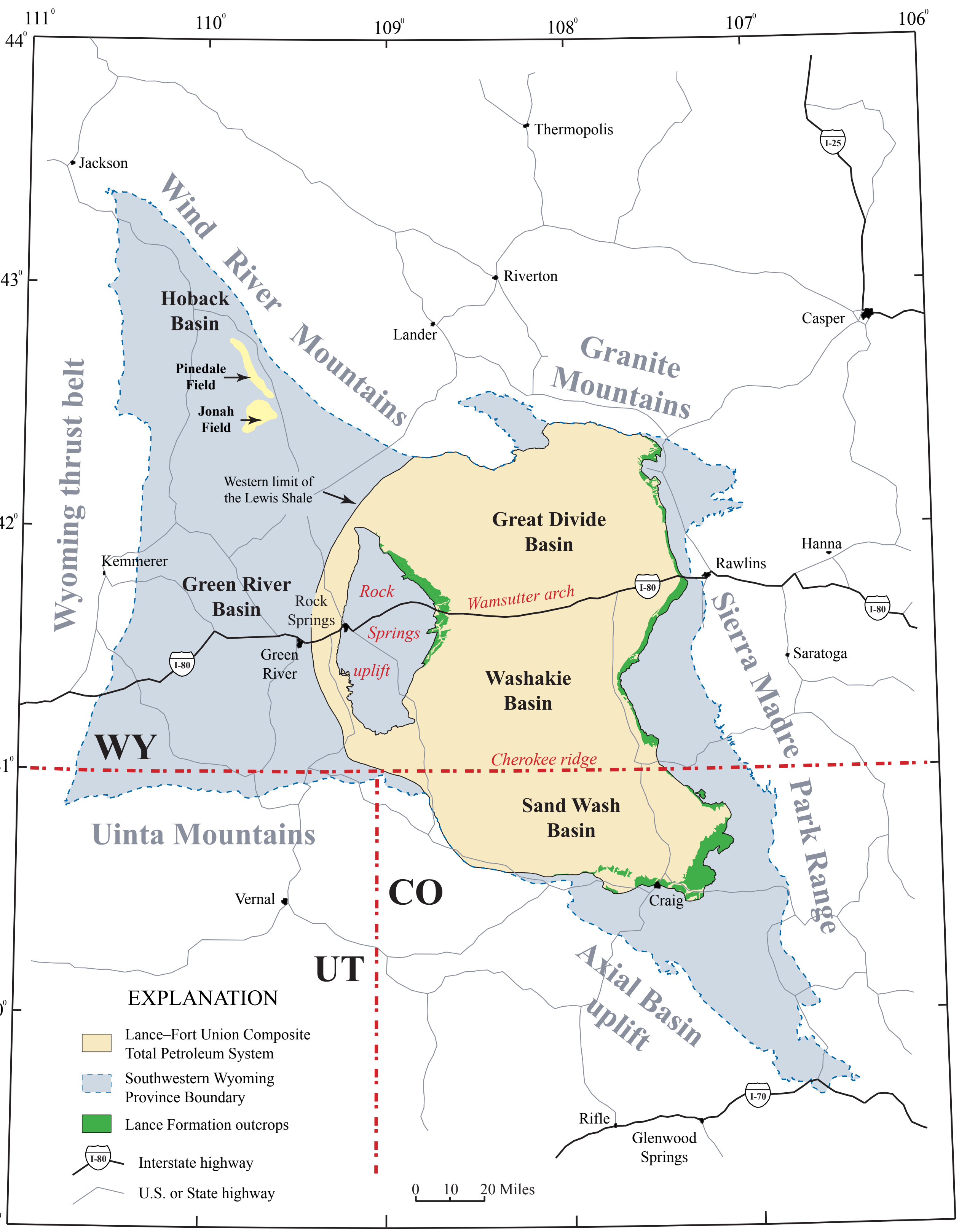

Figure 2. Location of the Lance–Fort Union Composite Total Petroleum System in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Lance Formation outcrops from Green (1992) and Green and Drouillard (1994).

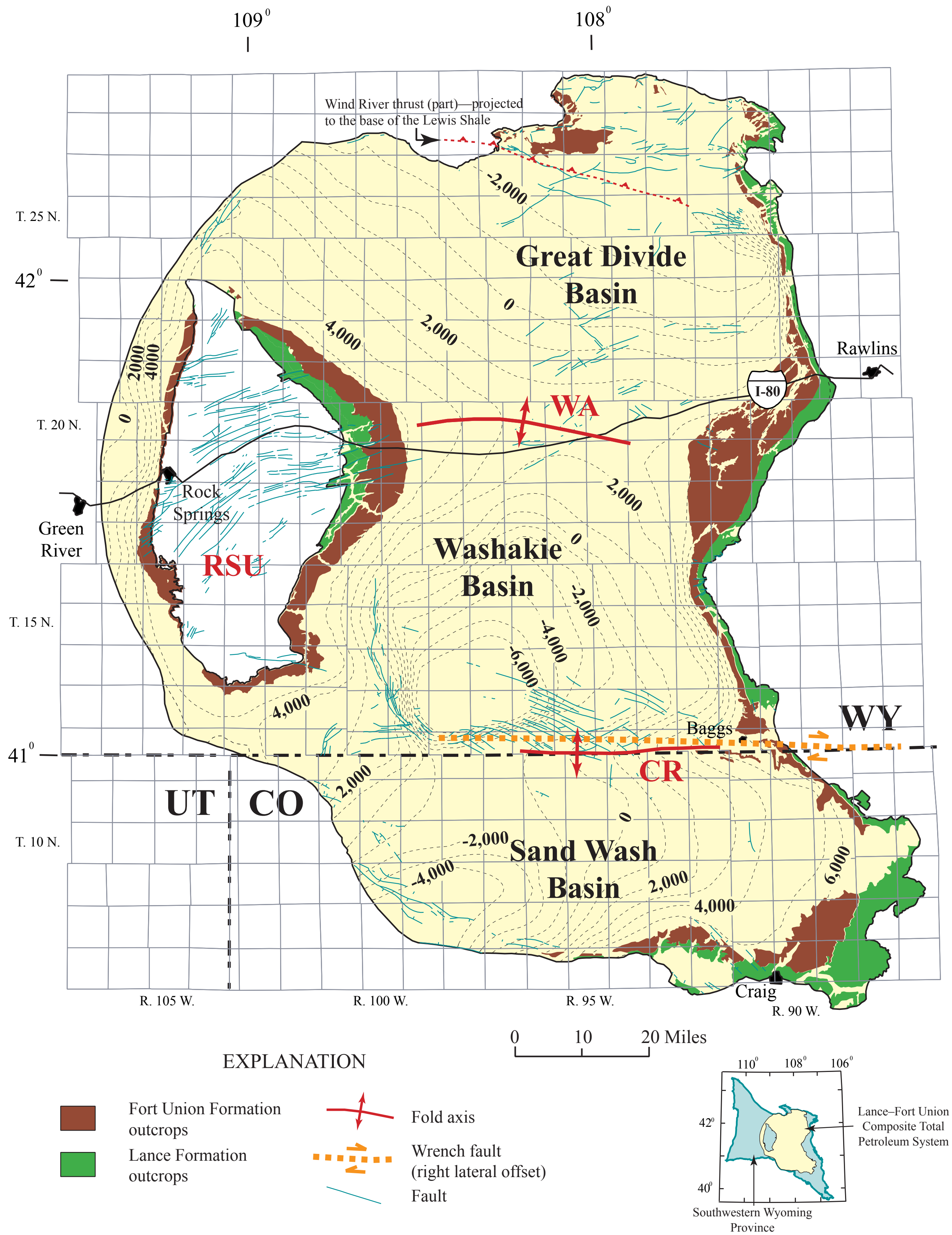

Figure 3. Generalized structure for the Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Structure contours drawn on top of the Lance Formation; contour interval 1,000 feet. CR, Cherokee ridge; WA, Wamsutter arch; RSU, Rock Springs uplift. Structure contours modified from Barlow and others, 1994. Location of wrench fault based on Bader (1987). Lance and Fort Union Formations outcrops from Green (1992) and Green and Drouillard (1994).

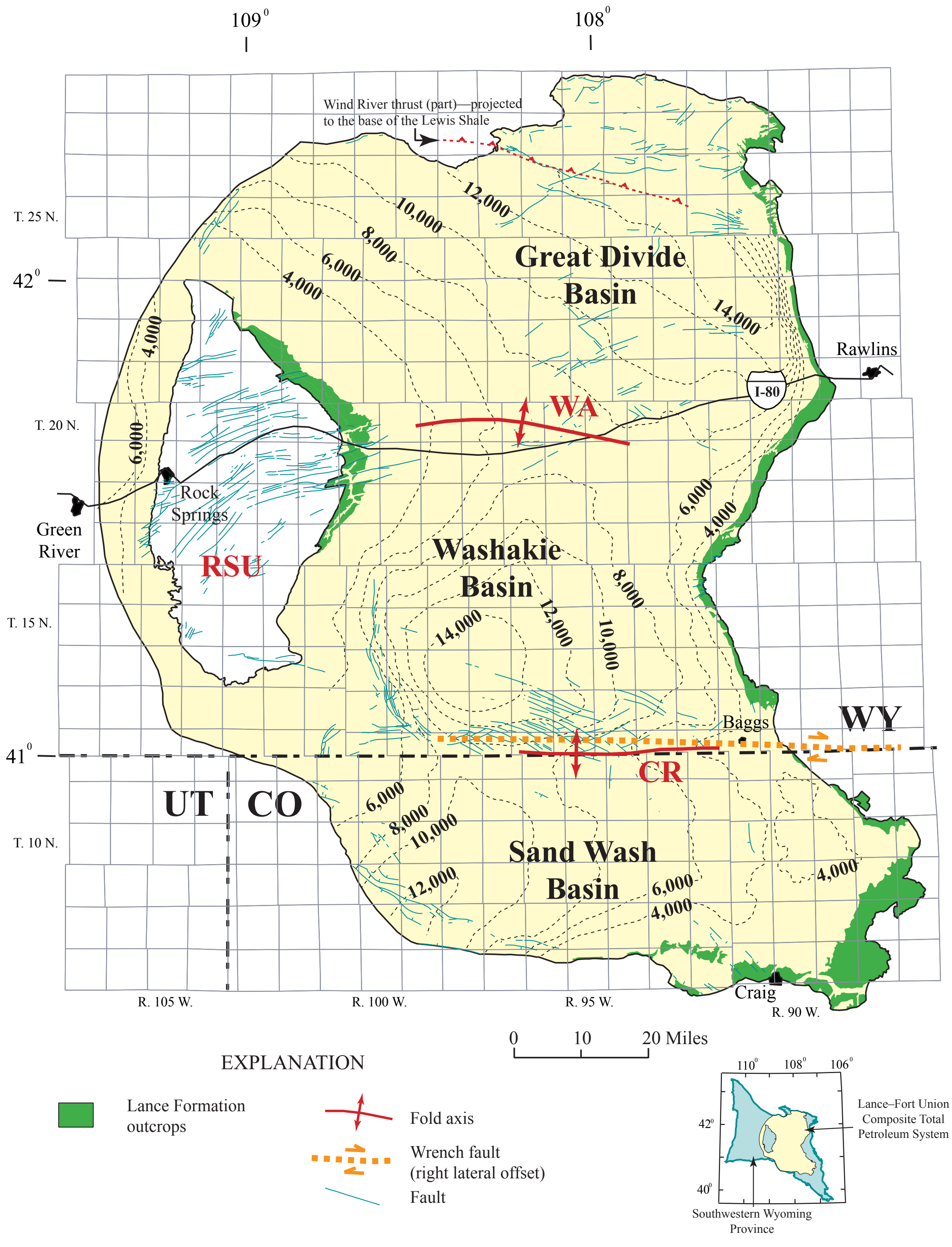

Figure 4. Estimated depth to the base of the Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Depth contours reflect estimated depth to the top of the Lewis Shale, which immediately underlies the Lance–Fort Union CTPS. Drill-hole data used in the construction of the map are from Petroleum Information/Dwights LLC (2001). Contour interval is 2,000 feet. Lance and Fort Union Formations outcrops from Green (1992) and Green and Drouillard (1994). CR, Cherokee ridge; WA, Wamsutter arch; RSU, Rock Springs uplift.

quantitatively assessed but are included in estimates of natural gas liquids within gas fields exceeding a minimum grown size of 3 billion cubic ft of gas (BCFG) (0.5 million barrels of oil equivalent [MMBOE]). Conventional accumulations are more maturely explored, whereas continuous accumulations are immaturely explored or essentially untested. Most of the historical production has targeted shallow sandstone reservoirs in conventional traps along Cherokee ridge and, to a lesser degree, on the Wamsutter arch (fig. 3). A limited number of wells have produced or are producing gas from sandstone reservoirs interpreted to be within continuous (basin-centered) accumulations in the Washakie and Great Divide Basins. These accumulations are at depths where overpressured and low-permeability reservoir conditions exist, and where thermal maturities in Lance and(or) Fort Union source rocks are above the maturity threshold for thermogenic gas generation. To date, there has been limited testing but no commercial production of coalbed gas from formations within the CTPS.

Acknowledgments

I would like to thank Laura Roberts (USGS) for her exhaustive efforts in generating key maps depicting structural, overburden, and thermal maturity trends and for her thoughtful interpretations of burial history and petroleum generation within the petroleum system. I would also like to thank Troy Cook (USGS) for his guidance on well recoveries and reservoir capacities that were critical to this evaluation. This manuscript also benefited greatly from the thoughtful reviews of Ronald Johnson (USGS), Mitchell Henry (USGS), Thomas Judkins (USGS), and Katharine Varnes (USGS), and I sincerely thank them for their efforts in this regard.

Stratigraphic Setting

In the succeeding discussions of stratigraphic units, informal nomenclature of Honey and Hettinger (1989), Hettinger and others (1991), and Hettinger and Kirschbaum (1991) is applied to unnamed latest Cretaceous and Paleocene units closely associated with the Lance and Fort Union Formations within the CTPS. However, the reader should note that this nomenclature has recently been revised (Honey and Hettinger, 2004) in order to formally incorporate previously unnamed latest Cretaceous strata within the Lance Formation and unnamed Paleocene units within the Fort Union Formation.

The Fox Hills Sandstone is generally less than 200 ft thick in outcrops along the eastern Great Divide and Washakie Basins (Gill and others, 1970), and in the subsurface, locally exceeds 300 ft in thickness (for example, see Hettinger and Kirschbaum, 1991). The formation typically contains superposed, coarsening-upwards successions of shale and fine-grained sandstone (Hettinger and others, 1991); thin coal beds are present locally. Shoreface (marginal marine) sandstone beds within the formation are potential reservoirs for hydrocarbon accumulation throughout the CTPS. The overlying Lance Formation varies in thickness from less than 1,000 ft in the southern Sand Wash Basin to 1,000–2,000 ft in the Washakie Basin, and to more than 5,000 ft in deeper parts of the Great Divide Basin. The Lance Formation includes hydrocarbon source rocks (especially coal) and potential hydrocarbon reservoirs in fluvial sandstone units.

A regional unconformity separates Upper Cretaceous and lower Tertiary strata within the CTPS, and in many areas, strata of latest Maastrichtian through earliest Paleocene age are absent due to erosion or nondeposition (for example, see Hettinger and others, 1991; Hettinger and Kirschbaum, 1991). The unconformity is identified by a conglomeratic horizon in the uppermost part of the “unnamed Cretaceous-Tertiary sandstone unit” of Hettinger and others (1991), which separates the Lance and Fort Union Formations; the conglomerate is generally within 100–200 ft of the base of the Fort Union. The Fort Union Formation represents fluvial and alluvial deposition coincident in great part with Laramide structural development of the basins and uplifts that are present within and surrounding the Southwestern Wyoming Province. The combined thickness of the Fort Union Formation and the unnamed Cretaceous-Tertiary sandstone unit varies from about 1,300 ft or less in the southern Sand Wash Basin, to more than 4,500 ft in the central Washakie Basin and in deeper areas of the Great Divide Basin (for example, see McDonald, 1975). The Fort Union contains potential source rocks (primarily coal) and fluvial sandstone reservoir rocks.

The contact between the top of the Fort Union Formation (here defined as the top of the “unnamed upper Paleocene unit” of Hettinger and others, 1991) and the overlying Wasatch Formation is generally unconformable along basin margins within the CTPS, but may be conformable in deeper basin areas (for example, see McDonald, 1975; Hettinger and Kirschbaum, 1991). As with the Fort Union Formation, the Wasatch Formation was deposited primarily in a fluvial/alluvial depositional setting during the latter stages of the Laramide orogeny. The Wasatch Formation is overlain by and intertongues with lacustrine shale units in the Green River Formation and arkosic sandstone and conglomerate in the Battle Spring Formation. As described previously, units of the Wasatch Formation and equivalent-age units in the Battle Spring Formation that are stratigraphically below the lowest lacustrine shale deposits in the Green River Formation are considered to be within the Lance–Fort Union CTPS. This would include the main body of the Wasatch Formation (for example, see Sears and Bradley, 1925; Masursky, 1962; Roehler, 1987a), the Red Desert Tongue (Pipiringos, 1961) and the Hiawatha Member (part) of the Wasatch Formation (Nightingale, 1930). The Hiawatha Member includes a lower part that may be equivalent to the Fort Union Formation (for example, see Masursky, 1962) and an upper part that may be equivalent to the Luman and Niland Tongues of the Green River and Wasatch Formations, respectively (Pipiringos, 1961). In the Washakie Basin, Roehler (1992) reports a thickness of 1,691 ft for the main body of the Wasatch Formation. Pipiringos (1961) reports a thickness of about 1,000 ft for the Red Desert Tongue of the Wasatch on the east flank of the Rock Springs uplift, and Masursky (1962) reports a combined thickness of about 3,500 ft for the main body of the Wasatch and the Battle Spring Formation in the south-central Great Divide Basin. Nightingale (1938) estimates a thickness of the 3,535 ft for the Hiawatha Member in the west-central part of Cherokee ridge in Colorado. The Wasatch and Battle Spring Formations contain fluvial and possibly marginal lacustrine rocks that are potential reservoirs for the accumulation of migrated hydrocarbon.

Source Rocks

Coal beds and associated noncoal, carbonaceous strata (shale, siltstone, and sandstone) within the Lance and Fort Union Formations are considered to be the primary source rocks for hydrocarbon generation within the Lance–Fort Union CTPS; these source rocks are composed of humic, Type-III organic matter, and thus are considered to be gas-prone (for example, see Meissner, 1984; Law and others, 1989; Law, 1996). Coal rank within the CTPS ranges from subbituminous to low volatile bituminous in deeper parts of the Washakie Basin (Tyler and others, 1995). Total organic carbon (TOC) in noncoal rocks with source-rock potential in Upper Cretaceous and Tertiary strata in the Southwestern Wyoming Province averages about 2.04 weight percent (Law, 1984), and TOC values from six noncoal samples in the Fox Hills Sandstone and Lance and Fort Union Formations range from 1.35 to 6.82 weight percent. Although these source rocks are considered to be gas prone, oil produced from Tertiary-age reservoirs in fields along Cherokee ridge is also interpreted as sourced by coal or coaly lithologies (Paul Lillis, U.S. Geological Survey, written commun., 2000). Coal in the Lance and(or) the Fort Union Formation is interpreted to be the source of this oil. Coal-bearing intervals in the Mesaverde Group are not considered a likely source because of their depth (10,000–12,000 ft) and the potential seal formed by the intervening Lewis Shale that would likely inhibit hydrocarbon migration from Mesaverde Group strata to reservoirs overlying the Lewis Shale in the Fort Union and Wasatch Formations.

Coal beds within the Lance and Fort Union Formations are present throughout most areas of the CTPS; however, the abundance of coal (cumulative coal thickness) in each formation is variable (fig. 5). In the Sand Wash and Washakie Basins, coal beds in the Lance are concentrated in the lower 300–500 ft of the formation. In the Great Divide Basin, north of the Wamsutter arch, the Lance Formation thickens significantly, and coal beds are more numerous and widely dispersed throughout the formation. Maximum depth to coal in the lower part of the Lance Formation exceeds 14,000 ft in the Washakie and Great Divide Basins, and is about 11,000–12,000 ft in deeper parts of the Sand Wash Basin. Cumulative coal thickness in the Lance is typically less than 30–40 ft, with minimum values of less than 10 ft and a maximum reported total coal thickness of 85 ft (Law, 1996).

Coal is volumetrically more abundant in the Fort Union Formation than in the Lance Formation. Maximum depth to coal beds in the Fort Union is about 9,000–10,000 ft in the Great Divide Basin, exceeds 12,000 ft in the Washakie Basin, and ranges from about 10,000 to 11,000 ft in the Sand Wash Basin. Individual coal bed thickness in the Fort Union is as much as 50 ft. Thick coal beds are concentrated in multiple coal zones within 1,000–1,200 ft above the base of the Fort Union Formation (lower coal-bearing unit; Tyler and others, 1995), and 8–10 coal beds are typically present throughout much of the central portion of the CTPS. Cumulative coal thickness in this interval exceeds 80 ft in areas along Cherokee ridge and the Wamsutter arch (fig. 5) and may exceed 100 ft in the Great Divide Basin (Tyler and others, 1995). Additional coal beds are present in the Cherokee coal zone and equivalent strata in the upper 200–500 ft of the formation (upper shaly unit; Beaumont, 1979; Tyler and others, 1995; unnamed upper Paleocene unit of Hettinger and others, 1991). Coal beds in this interval tend to be more lenticular than coal beds in the lower coal-bearing interval of the formation (for example, see Hettinger and others, 1991).

Source Rock Maturation Summary

Source rocks in the basal part of the Lance Formation have reported thermal maturity (R_o) values ranging from less than 0.50 percent to more than 1.60 percent, based on direct measurements of vitrinite reflectance from Lance coal and carbonaceous shale beds, or extrapolated from vitrinite reflectance values for the top of the Lewis Shale. Measured R_o values for coal and carbonaceous source rocks near the base of the Fort Union Formation range from less than 0.50 percent to about 1.53 percent. Within the CTPS, the highest reported R_o values for the Lance and Fort Union Formations were measured at depths from about 12,000 to 13,000 ft in the deep, south-central part of the Washakie Basin (Law, 1984).

The extent of mature source rocks in the CTPS (fig. 6) is defined as that area in which thermal maturity (R_o) values at the base of the Lance Formation are estimated to be 0.60 percent or greater. This R_o value was used to define the primary "pod" of mature source rock within the CTPS because of the potential for source rocks composed of Type-III organic matter to generate hydrocarbons at thermal maturity (R_o) levels ranging from about 0.50 to 0.60 percent (see, for comparison, Levine, 1993; Rice, 1993; Roberts and others, Chapter 3, this volume). Thermal maturity data limitations in outcrop areas precluded projection of a 0.50 percent R_o isoreflectance boundary, so the 0.60 percent R_o value was used as the estimated limit of mature source rocks. In addition, although some gas is generated during early maturation stages (R_o of 0.50–0.60 percent), significant thermal gas generation

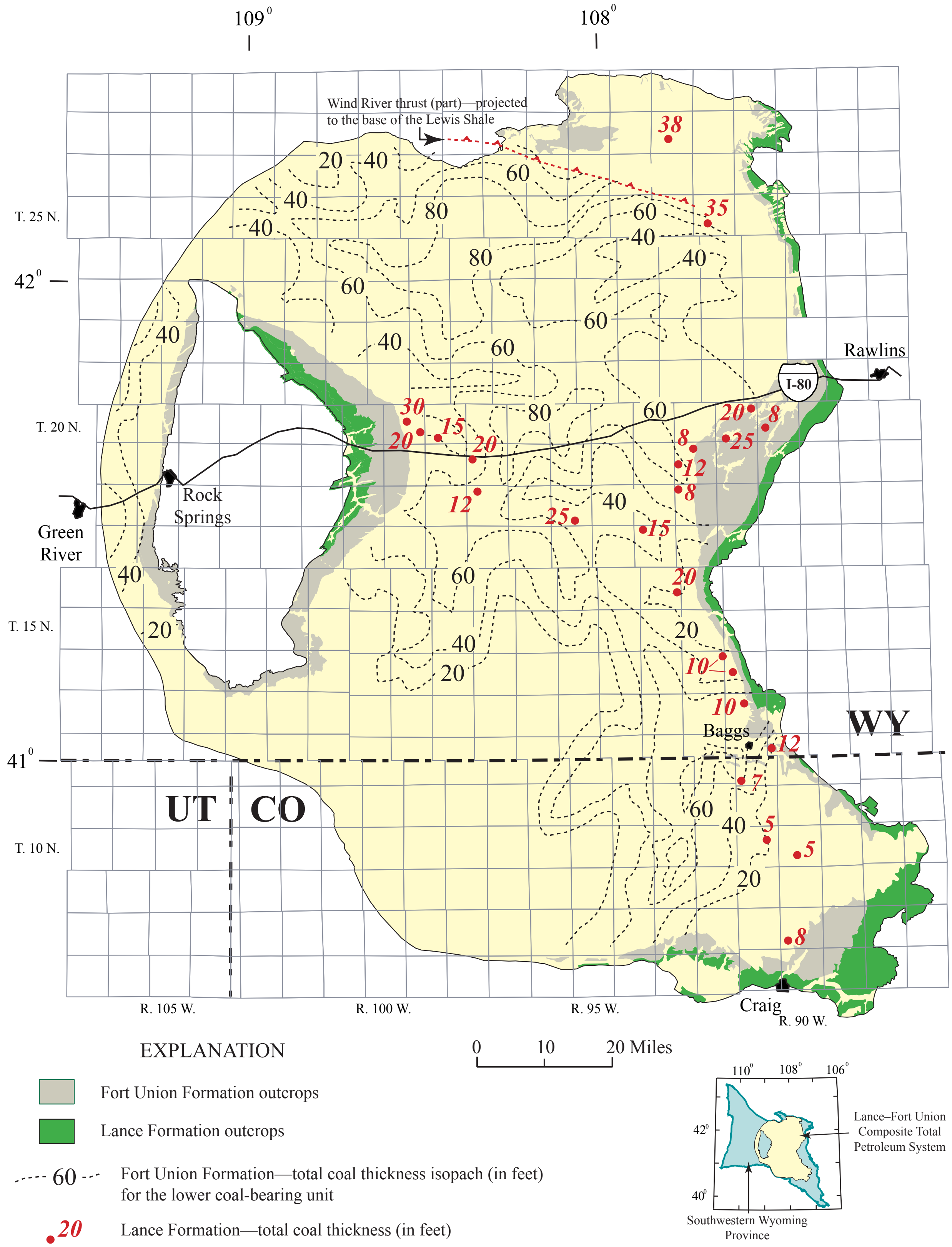

Figure 5. Total coal thickness for the lower part of the Lance and Fort Union Formations in selected areas of the Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Fort Union Formation total coal isopachs modified from Tyler and others (1995); contour interval 20 feet. Lance and Fort Union Formation outcrops from Green (1992) and Green and Drouillard (1994).

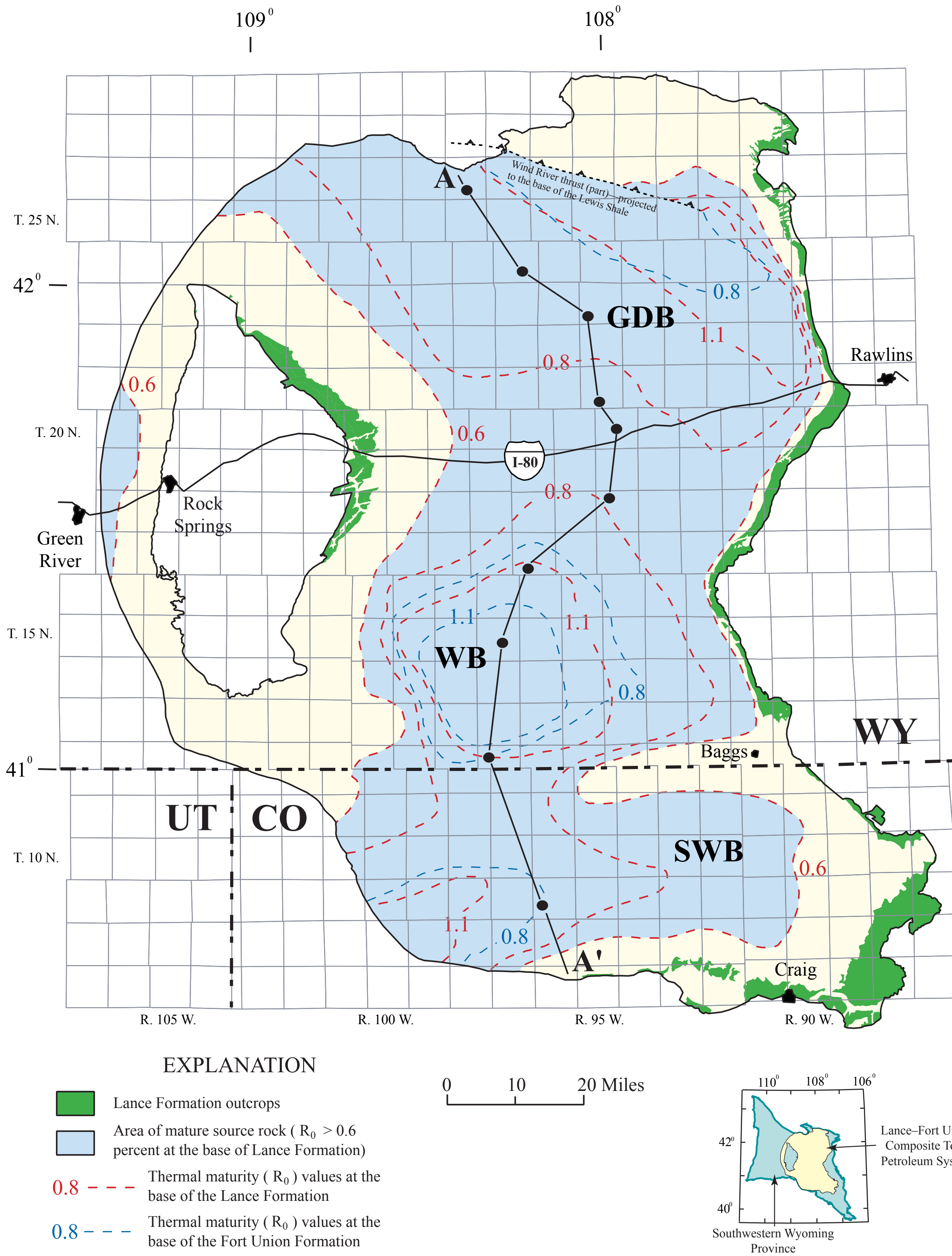

Figure 6. Estimated thermal maturity (vitrinite reflectance values in percent R_0) for horizons near the base of the Lance Formation and near the base of the Fort Union Formation, Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Thermal maturity based on vitrinite reflectance data in Law (1984), and Pawlewicz and Finn (2002). Lance Formation outcrops from Green (1992) and Green and Drouillard (1994). GDB, Great Divide Basin; WB, Washakie Basin; SWB, Sand Wash Basin. A–A' is location of wells and cross section shown in figure 7.

in Type-III organic matter is thought to occur at higher R_o levels of about 0.73–0.80 percent (for example, see Law, 1984; Meissner, 1984; Johnson, 1989), and the threshold for sufficient gas generation to induce overpressure is interpreted to be at an R_o level ranging from 0.80 percent to about 1.0 percent ("peak" gas generation; Roberts and others, Chapter 3, this volume). Based on these criteria, the primary areas of thermogenic gas generation within the CTPS are interpreted to be in deeper portions of the Sand Wash, Washakie, and Great Divide Basins, where source rocks near the base of both the Lance and Fort Union Formations have reached or exceeded an R_o level of 0.80 percent (figs. 6 and 7).

Charts summarizing the timing of gas generation and other related events in each assessment unit in the Lance-Fort Union CTPS are shown in figures 8–11. The timing of gas generation is based primarily on vitrinite reflectance data from Law (1984) and Pawlewicz and Finn (2002), and on interpretations of burial history (Roberts and others, Chapter 3, this volume) for the Adobe Town well in the deep, central portion of the Washakie Basin (section 20, T. 15 N., R. 97 W.), and the Eagles Nest well in the deep, central part of the Great Divide Basin (section 29, T. 25 N., R. 91 W.). Using the 0.50-percent R_o level as the lower maturity limit for gas generation, the onset of gas generation from source rocks in the lower part of the Lance Formation is estimated at 53 million years ago (m.y.a.) in the Washakie Basin, and at 58 m.y.a. in the Great Divide Basin. Peak gas generation (R_o level of 0.80 percent) in the lower Lance in both basins occurred from about 47 to 48 m.y.a. Source rocks in the Fort Union Formation began generating thermogenic gas about 51 m.y.a. in the central Washakie Basin and about 47 m.y.a. in the central Great Divide Basin. In the Washakie Basin (Adobe Town well), peak gas generation in the Fort Union Formation occurred about 44 m.y.a. In the Great Divide Basin, however, data from the Eagles Nest well indicate that source rocks in the Fort Union are just at or slightly below peak thermal maturity (R_o = 0.80 percent).

The presence of gas in low-permeability, overpressured reservoirs in the Fox Hills, Lance, and Fort Union Formations in certain areas of the Great Divide and Washakie Basins (for example, see Law and others, 1989; Scotia Group, 1993) may indicate the presence of basin-centered gas accumulations within the CTPS. Uplift and cooling have significantly reduced the rate of gas generation, although some generation might still be occurring where R_o values in Lance and Fort Union Formation source rocks are greater than 0.80 percent, and where present-day subsurface temperatures in the coal-bearing intervals exceed about 200°F (for example, see Law, 1984; Spencer, 1987). Petroleum-generation kinetic modeling applied by Roberts and others (Chapter 3, this volume) also supports the idea that gas generation in Lance and Fort Union source rocks is continuing at present in deeper areas of the Washakie and Great Divide Basins.

Hydrocarbon Migration Summary

Gas expelled from deeply buried coal and carbonaceous strata migrated relatively short distances into low-permeability (tight) sandstone reservoirs in close proximity to mature (R_o > 0.80 percent) source rocks (Law, 1984). Gas that migrated into nearby low-permeability reservoirs may have followed fractures that formed during gas generation. Where source-rock maturity levels exceed R_o values of about 1.10 percent (fig. 6), generation and migration may have resulted in the development of basin-centered accumulations containing gas-saturated reservoirs in deeper basin areas. In areas surrounding basin-centered accumulations, where R_o levels are between 0.80 and 1.10 percent, gas migration may have charged nearby reservoirs less completely, resulting in a combination of water-wet and gas-saturated reservoirs (transition zone; for comparison, see Johnson and others, 1987).

Hydrocarbons in the CTPS also migrated vertically and laterally (updip) into shallow (above 8,000-ft depth) reservoirs in conventional accumulations along basin margins and on intervening structural arches. Because of the generally discontinuous nature of fluvial sandstone units, and the presence of thick, relatively impermeable mudstone and siltstone successions within the Lance, Fort Union, and Wasatch Formations, faults or fracture systems may have been critical for successful hydrocarbon migration from source rocks at depth into shallow conventional reservoirs, particularly along Cherokee ridge (fig. 3). Updip migration of hydrocarbons into conventional reservoirs in the Fox Hills Sandstone may have been aided by the fairly continuous geometry of the shoreface and marginal marine sandstone successions characterizing this formation.

Reservoir Rocks

Primary reservoirs in the Lance–Fort Union CTPS are fluvial sandstone deposits in the Lance, Fort Union, and Wasatch Formations, with additional reservoirs in marginal marine sandstone in the Fox Hills Sandstone. Coal beds, which were described in the previous discussion of source rocks, are the primary reservoirs for potential coalbed-gas accumulations.

Coarsening upward successions in the Fox Hills Sandstone include interbedded sandstone, siltstone, shale, and coal; sandstone beds capping these successions are typically very fine to medium grained, and as thick as 70 ft (Hettinger and Kirschbaum, 1991). Fluvial sandstone beds in Lance and Fort Union strata overlying the Fox Hills range from fine grained to conglomeratic and vary from isolated, lenticular beds less than 10–15 ft thick to amalgamated (multistoried) sandstone intervals that are hundreds of feet thick. The lower part of the Lance Formation includes abundant fine-grained lithologies (mudstone and siltstone), and sandstone beds as thick as 20 ft are rare. The upper part of the Lance is more sand rich and contains amalgamated, laterally discontinuous sandstone units

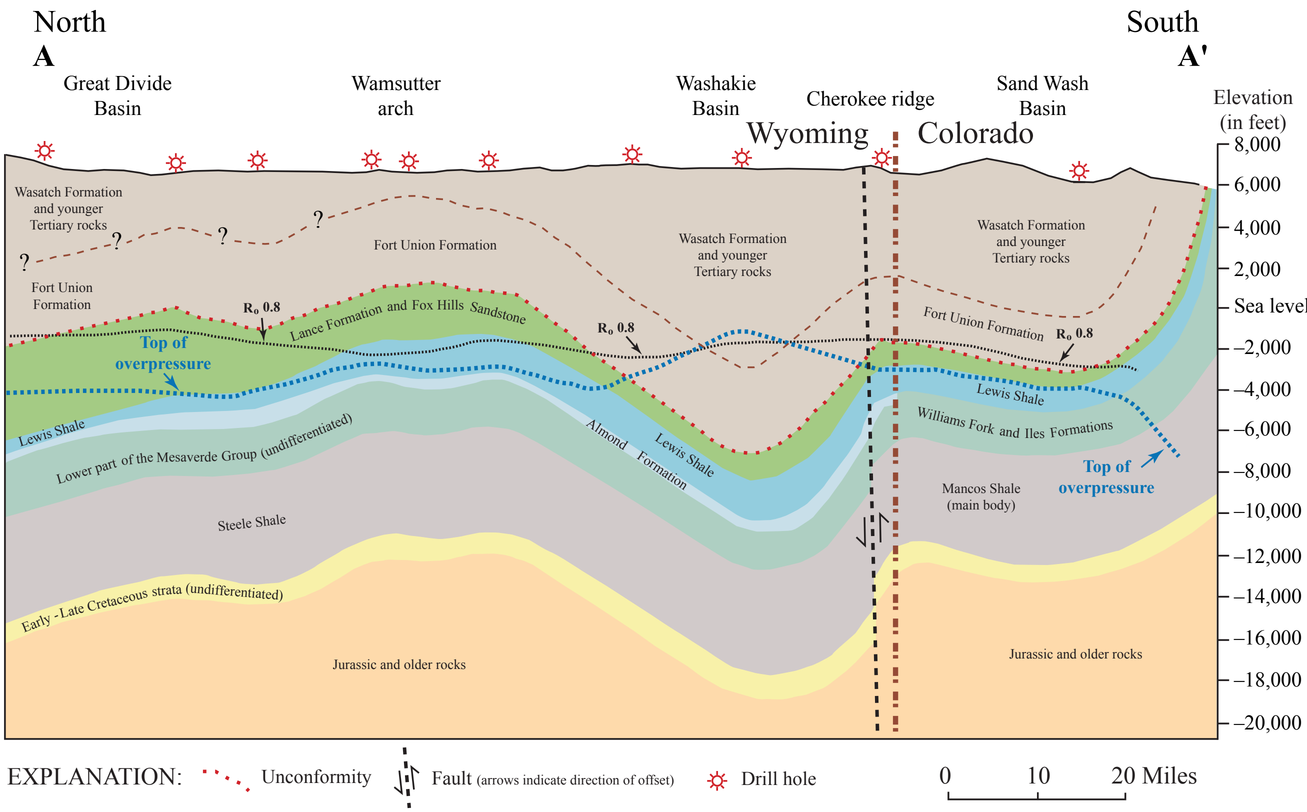

Figure 7. Schematic north-south cross section showing depth to top of gas-bearing, overpressured strata, and estimated depth to the 0.8 percent isoreflectance (Ro) horizon in the Great Divide, Washakie, and Sand Wash Basins, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Location of cross section is shown in figure 6. Modified from Law and others (1989).

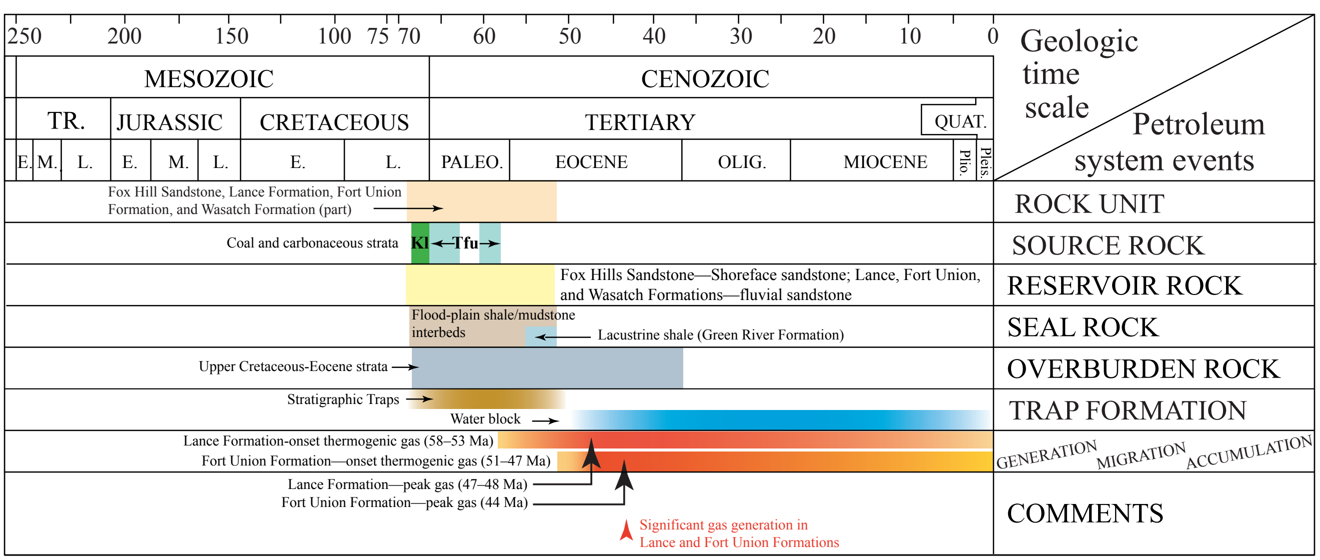

Figure 8. Events chart showing the interpreted timing of elements and processes related to gas generation and accumulation in the Lance–Fort Union Continuous Gas Assessment Unit (50370861), Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Water block refers to hydrocarbon trapping by water saturation and capillary seal. Onset of thermogenic gas generation and timing of peak gas generation are from Roberts and others (Chapter 3, this volume). Kl, Lance Formation; Tfu, Fort Union Formation; TR., Triassic; E., Early; M., Middle; L., Late; Paleo., Paleocene; Olig., Oligocene; Plio., Pliocene; Pleis., Pleistocene; Quat., Quaternary. Peak generation refers to maximum rate of gas generation. Events chart format modified from Magoon and Dow (1994).

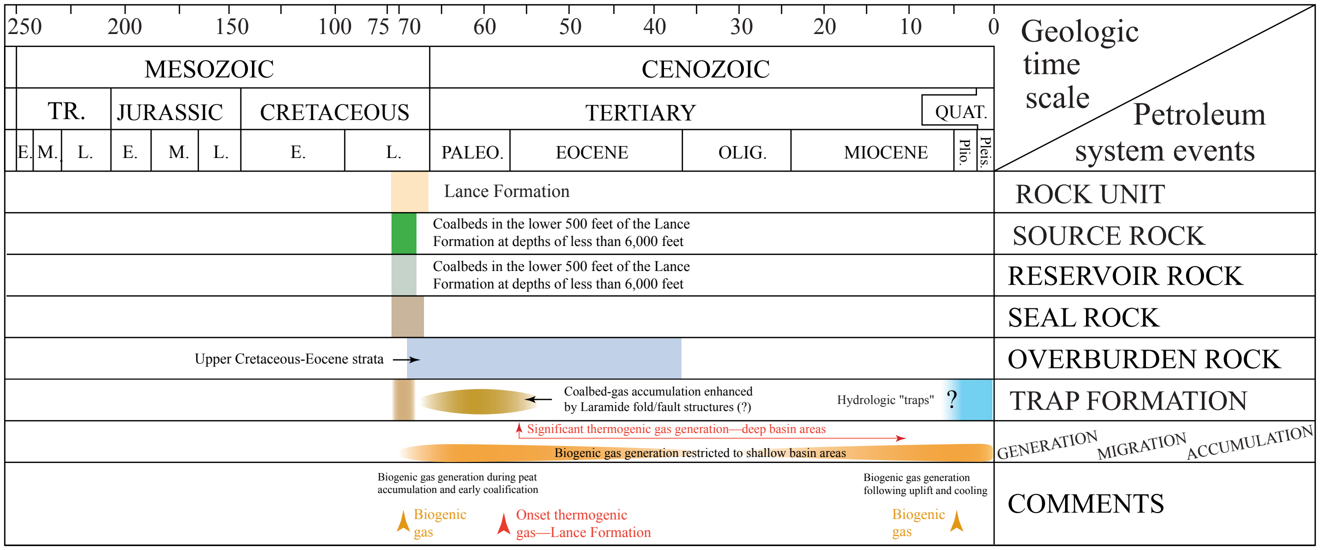

Figure 9. Events chart showing the interpreted timing of elements and processes related to gas generation and accumulation in the Lance Coalbed Gas Assessment Unit (50370881), Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. TR., Triassic; E., Early; M., Middle; L., Late; Paleo., Paleocene; Olig., Oligocene; Plio., Pliocene; Pleis., Pleistocene; Quat., Quaternary. Onset of thermogenic gas generation is from Roberts and others (Chapter 3, this volume). Events chart format modified from Magoon and Dow (1994).

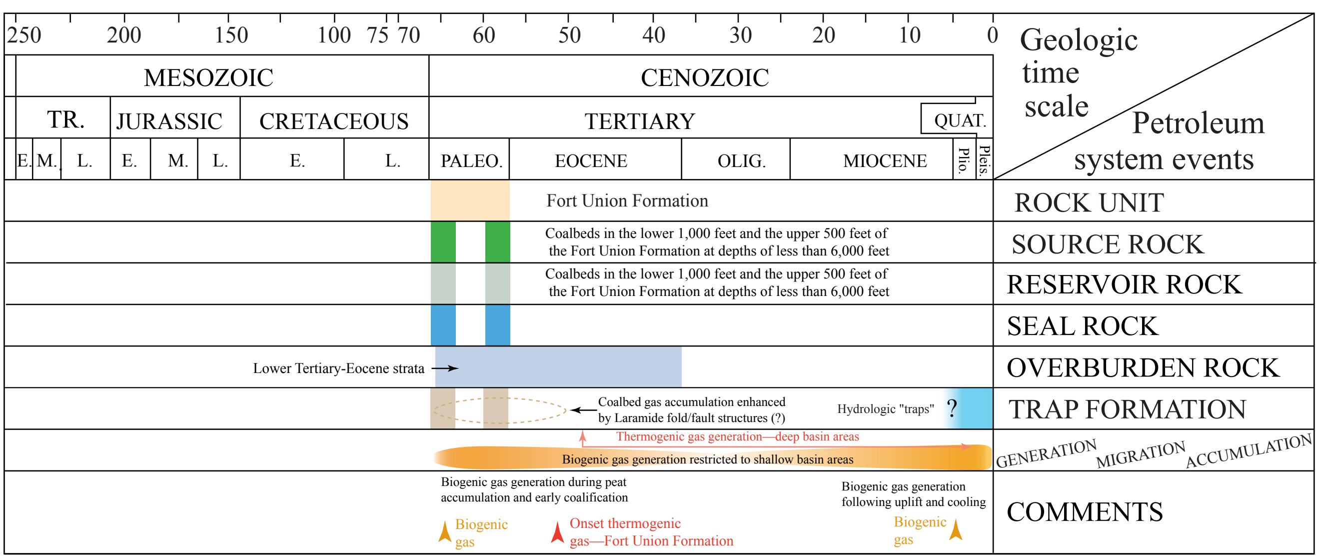

Figure 10. Events chart showing the interpreted timing of elements and processes related to gas generation and accumulation in the Fort Union Coalbed Gas Assessment Unit (50370882), Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Onset of thermogenic gas generation is from Roberts and others (Chapter 3, this volume). TR., Triassic; E., Early; M., Middle; L., Late; Paleo., Paleocene; Olig., Oligocene; Plio., Pliocene; Pleis., Pleistocene; Quat., Quaternary. Events chart format modified from Magoon and Dow (1994).

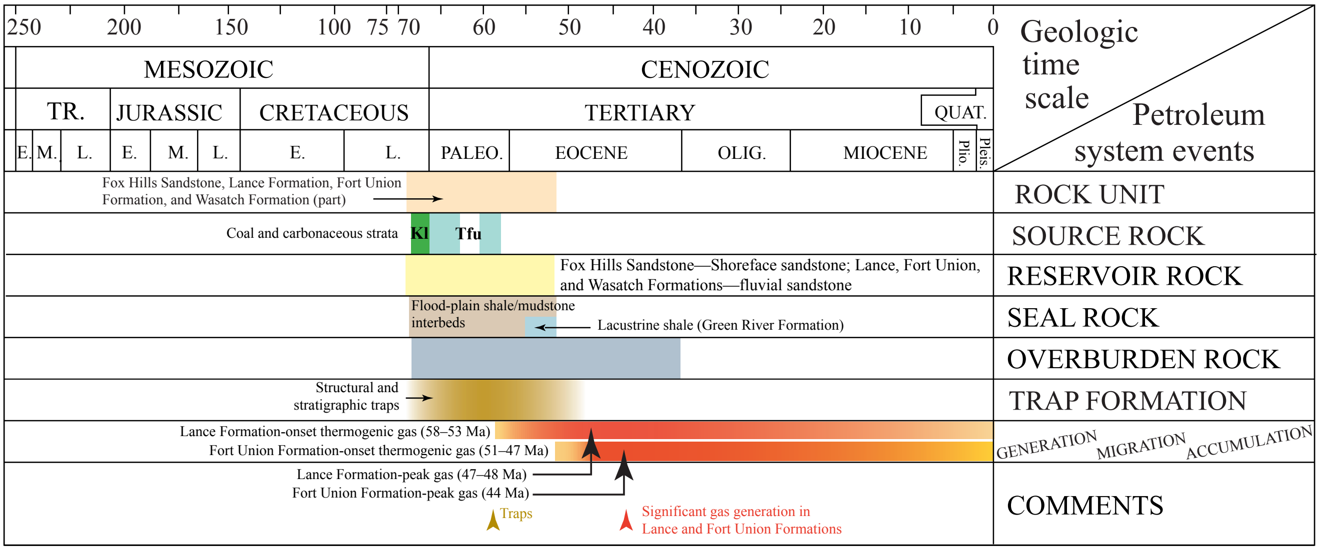

Figure 11. Events chart showing the interpreted timing of elements and processes related to hydrocarbon (gas) generation and accumulation in the Lance–Fort Union Conventional Oil and Gas Assessment Unit (50370801), Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Onset of thermogenic gas generation and timing of peak gas generation are from Roberts and others (Chapter 3, this volume). Peak generation refers to maximum rate of gas generation. Kl, Lance Formation; Tfu, Fort Union Formation; TR., Triassic; E., Early; M., Middle; L., Late; Paleo., Paleocene; Olig., Oligocene; Plio., Pliocene; Pleis., Pleistocene; Quat., Quaternary. Events chart format modified from Magoon and Dow (1994).

as thick as 80 ft (for example, see Hettinger and Kirschbaum, 1991). Overlying the Lance Formation throughout much of the CTPS is a thick, areally extensive amalgamated sandstone body designated as the unnamed Cretaceous-Tertiary sandstone unit (Hettinger and others, 1991). This unit varies from fine-grained sandstone to conglomerate and exceeds 1,000 ft in thickness in the eastern Washakie and southern Great Divide Basins.

Fluvial sandstone units are also abundant in the overlying Fort Union Formation, with individual sandstone beds exceeding 20 ft in thickness and amalgamated sandstone bodies as thick as 100 ft. An additional pervasive amalgamated sandstone unit (basal sandstone zone of the unnamed upper Paleocene unit; Hettinger and others, 1991) overlies the lower part of the Fort Union Formation in the north-central Washakie and southern Great Divide Basins. This sandstone body is primarily coarse grained to conglomeratic and is as thick as 1,000 ft in the northeastern Washakie Basin. The upper part of the Fort Union Formation (Cherokee coal zone and equivalent strata in the unnamed upper Paleocene unit; Hettinger and others, 1991) and the overlying Wasatch Formation include more fine-grained lithologies, and sandstone beds in these intervals tend to be more isolated and lenticular.

In conventional gas fields along Cherokee ridge (fig. 3), reservoir sandstone porosities range from 12 to 39 percent and average about 22 percent; permeability ranges from less than 0.50 to more than 1,500 millidarcies (mD). Average pay thickness is about 20–25 ft; however, production from multiple zones can result in a total pay thickness exceeding 200 ft (Cardinal and Hovis, 1979; Farmer, 1979; Lehman, 1979; Cardinal, 1992a–e).

Data on reservoir characteristics in overpressured, low-permeability gas reservoirs in the CTPS are limited. Cumulative, net pay for reservoirs associated with these accumulations are estimated to be as thick as 250 ft in the combined Fox Hills and Lance and as thick as 500 ft in the Fort Union in the central Washakie Basin (Scotia Group, 1993). Porosities based on core evaluation of sandstone samples in the Fox Hills, Lance, and Fort Union Formations in the deep Washakie Basin range from less than 5 percent to about 15 percent; permeability is low (commonly less than 1 mD), with the anticipation that many reservoirs will likely have permeabilities of 0.1 mD or less (Scotia Group, 1993).

Hydrocarbon Traps and Seals

Primary traps for hydrocarbon accumulation of thermogenic gas and oil in the Lance–Fort Union CTPS include structural, stratigraphic, or combined structural-stratigraphic traps associated with relatively shallow (less than 8,000 ft deep) conventional accumulations, and stratigraphic traps and the process of water block associated with deeper, basin-centered gas accumulations. Retention of gas in coalbed reservoirs may depend to some degree on “hydrologic” traps, whereby contained water and associated hydrostatic pressure within the coal prohibits desorption and leakage of coalbed gas; impermeable lithologies in contact with coal beds could also help to seal free gas within fractures and coal cleats.

Structural traps and combined structural/stratigraphic traps associated with conventional gas and oil accumulations are best exhibited along Cherokee ridge (fig. 3). Structural development of the arch stemmed primarily from displacement along an east-west-trending wrench fault system in which movement occurred intermittently from Late Cretaceous through Miocene(?) time (Bader, 1987). En-echelon, anticlinal folds that formed during Laramide structural development of Cherokee ridge provided traps for hydrocarbon accumulation. Structural closure in individual folds on the arch can range from about 100 ft or less at the surface to several hundreds of feet at depth in more productive fields (for example, see Biggs and Espach, 1960; Millison, 1965; Collins, 1971; Parker and Bortz, 2001). Faults dissect many of these folds, offsetting Cretaceous and Tertiary strata in the subsurface and also providing potential hydrocarbon traps where faults juxtapose porous units with impermeable lithologies, or where faults provide updip closure in folds (Bader, 1987). Lenticular fluvial sandstone beds that are prevalent in the Lance, Fort Union, and Wasatch Formations provide additional stratigraphic traps within this overall structural setting, resulting in multiple pay intervals that are highly variable in thickness and lateral continuity. Stratigraphic trapping may be enhanced in lenticular sandstone beds due to stratigraphic pinch-out and the presence of seals formed by impermeable shale and mudstone that commonly surround these sandstone bodies. In many or most of the conventional fields on Cherokee ridge, the combination of structural and stratigraphic traps is considered as the key factor for significant hydrocarbon accumulation.

Primary trapping mechanisms in basin-centered accumulations are thought to be stratigraphic trapping, as described above for fluvial sandstone reservoirs, and the process of water block. In basin-centered accumulations, water production is anticipated to be negligible, and low-permeability (tight) reservoirs that typify these accumulations are abnormally pressured and potentially gas saturated (for example, see Masters, 1979; Law, 1996; Law, 2002). In normally pressured strata that are updip from and overlying the basin-centered accumulation, gas saturation decreases and water saturation increases. Where water saturation is high, low-permeability (tight) sandstone reservoirs may become essentially impervious to gas flow, and an effective seal (water block) is formed, confining gas-saturated strata to the deeper, central portions of the basin-centered accumulation (for example, see Masters, 1979).

Lacustrine shale units in the Green River Formation overlying the Lance–Fort Union CTPS may also have acted as more areally extensive seals, inhibiting the vertical migration of gas into Eocene-age and younger rocks throughout much of the Washakie Basin and in more limited areas of the Great Divide and Sand Wash Basins.

Assessment Units—Lance–Fort Union Composite Total Petroleum System

The Lance–Fort Union Composite Total Petroleum System includes one continuous gas assessment unit (50370861), two hypothetical coalbed-gas assessment units (50370881 and 50370882), and one conventional gas and oil assessment unit (50370801). Total undiscovered oil resources, which are minor with respect to gas resources, were not quantitatively assessed in this study. However, all liquid hydrocarbons within gas fields of a grown size larger than 3 billion cubic feet of gas (BCFG) are included in the natural gas liquids (NGL) estimates.

50370861: Lance–Fort Union Continuous Gas Assessment Unit

The Lance–Fort Union Continuous Gas Assessment Unit (AU) includes areas where thermal maturity (R_o) values are 0.8 percent or greater in potential source rocks near the base of the CTPS (Fox Hills Sandstone and lower Lance Formation). The AU boundary is defined by the surface (vertical) projection of the 0.8 percent isoreflectance (R_o) line estimated for the top of the Lewis Shale (Hettinger and Roberts, Chapter 9, this volume), which immediately underlies the Lance–Fort Union CTPS. At this level of thermal maturity, gas-prone source rocks (Type-III organic matter) have the ability to generate and expel significant amounts of gas (Meissner, 1984; Law, 1984; Roberts and others, Chapter 3, this volume), and for this reason, the potential for gas accumulation exists throughout the entire AU. However, in other Rocky Mountain basins, gas accumulations in areas where thermal maturity ranges from about 0.8 to 1.1 percent have been considered to be within a "transition zone" that generally includes a combination of gas-charged and water-wet reservoirs (for example, see Johnson and others, 1987; Johnson and Roberts, 2003). Thus, although the Lance–Fort Union Continuous Gas AU might contain gas-charged reservoirs throughout its extent, fully gas-saturated reservoirs may be more likely to exist in those areas where R_o values near the base of the CTPS exceed about 1.0–1.10 percent (fig. 6).

The AU encompasses about 2,444,000 acres (3,800 mi^2). Variability in the estimated assessment unit area (minimum-median-maximum extent; Appendix A) relates primarily to the limited number of measured R_o values and the need to extrapolate the 0.80 percent isoreflectance line through areas where R_o data are absent. Extrapolation of R_o values in these areas is based on structural trends at the top of the Lewis Shale. The stratigraphic base of the assessment unit is placed at the contact between the Fox Hills Sandstone and underlying Lewis Shale. The top of the assessment unit is generally defined by an 8,000-ft depth cutoff, such that in most areas, only those CTPS stratigraphic units (source and reservoir rocks) above the base of the Fox Hills Sandstone and at depths exceeding 8,000 ft are considered to be within the AU. This depth cutoff is based on the concept that the top of overpressure (reservoir pressure gradients greater than 0.43 psi/ft) and depth to thermal-maturity levels equaling an R_o of 0.8 percent, factors which are considered to define the top of the continuous gas accumulation, typically range from about 8,000 to 10,000 ft deep in the Southwestern Wyoming Province (for example, see Law, 1984; Law and others, 1989). Exceptions to this depth cutoff include the Barrel Springs field and Bitter Creek unit in the Washakie Basin (fig. 12), where the projected depth to an R_o of 0.80 percent at the base of the Fox Hills Sandstone (base of the CTPS) is less than 8,000 ft. In these areas, gas production from the Fox Hills Sandstone and overlying Lance Formation was also included within the continuous gas accumulation.

Primary reservoirs in the AU are fluvial sandstone intervals, which are sealed locally by relatively impermeable mudrock that surrounds many of the sandstone beds. Pressure gradients calculated from drill-stem tests in sandstone beds within the AU indicate normal pressure to moderate overpressure (as high as 0.55 psi/ft) in the Fox Hills Sandstone and Lance Formation, and normal pressure to very slight overpressure (as high as 0.48 psi/ft) in the Fort Union Formation (Philip Nelson, U.S. Geological Survey, written commun., 2000). Law and others (1989) indicate that in the deepest part of the Great Divide Basin, the Fox Hills Sandstone and lower Lance Formation may include as much as 2,000–3,000 ft of overpressured, gas-bearing strata. In the deep Washakie Basin, the same study indicates that the top of gas-bearing, overpressured strata extends upward through the Fort Union Formation. However, the projected depth to the 0.80 percent R_o horizon in certain areas of the AU varies significantly from the projected top of overpressure (fig. 7), suggesting that, although the entire AU contains thermally mature source rocks for gas generation, overpressured strata within the CTPS may be related to other factors besides thermal maturity.

An estimated 110 wells are considered to have tested the AU (Appendix A). This total includes wells that are producing or have produced gas from the AU, dry holes that terminate within the AU, and wells that had drill-stem tests within the AU, based on data that are current through the last quarter of 2001 (IHS Energy Group, 2001) (fig. 13). Of the 110 wells, 48 were identified as gas producers. However, key information such as perforation depths and pressure data, needed to verify that all of the gas production is representative of the continuous accumulation, was not available for certain wells, and the actual number of producing gas wells is probably less than 48. Of the 48 identified gas wells, production data were available for only 15 wells (IHS Energy Group, 2001). Of these 15 wells, 8 are now abandoned or shut-in (Wyoming Oil and Gas Conservation Commission, 2002). Fields that include wells interpreted to be producing gas from the AU are shown in figure 12. Most of the fields include only one or two wells. Powder Wash, however, has 22 wells that have total depths exceeding 8,000 ft and could be producing gas from this AU. However, available production data for that field applied solely to shallow, conventional reservoirs and therefore were not used in the analysis of the AU. With the exception of the relatively shallow production (above 8,000 ft-depth) from four wells in the Barrel Springs field and Bitter Creek Unit, lowest perforation depths for producing horizons in the AU range from 8,500 ft to more than 13,400 ft (IHS Energy Group, 2001).

The paucity of data pertaining to reservoir and production characteristics within the AU necessitated that comparative data derived from other continuous (tight-gas) accumulations be used as analogs for completion of the assessment. Analogs used include the Greater Natural Buttes field in the Uinta Basin, the Rulison, Parachute, and Grand Valley fields in the Piceance Basin (for example, see Johnson and Roberts, 2003) and the Jonah and Pinedale fields (fig. 2) in the Hoback Basin area of the Southwestern Wyoming Province (for example, see Finn and others, Chapter 10, this volume). Gas production in these analog areas is primarily from low-permeability, fluvial sandstone reservoirs in the Mesaverde Group (Piceance Basin), the Lance and Fort Union Formations (Pinedale and Jonah fields), and the Wasatch Formation (Uinta Basin). In general, these analogs were useful for estimating (1) the drainage area for untested cells, and (2) the total recovery for untested cells with potential for additions to reserves. Because Jonah field is somewhat unique in terms of the geologic setting and production stimulation successes, (for example, see Montgomery and Robinson, 1997; Warner, 2000), it was not used directly as an analog for estimating total recovery per cell of untested cells in the Lance–Fort Union Continuous Gas AU (Appendix A). Data from Jonah field, however, are presented in the ensuing discussion for comparison with data from the other fields.

Because fluvial reservoirs are commonly discontinuous, and because reservoir porosity and permeability are generally low in continuous accumulations, the drainage area surrounding a well bore is likely to be influenced by natural fractures. In areas where no fractures are present and reservoirs are tight (less than 0.1 mD), effective drainage areas might be quite limited. For this reason, a minimum cell size of 20 acres was applied to untested cells in the AU to account for this scenario. The 80-acre median estimate used in this assessment is based on the idea that some degree of fracture permeability is likely in many areas of the AU, particularly in and near larger Laramide structures. At this spacing, the minimal degree of interconnectedness between fluvial reservoirs should diminish the potential for interference between adjacent wells, even where fracture permeability increases the effective drainage. The maximum drainage area applied to untested cells is 200 acres, and the effective drainage of tight reservoirs at this spacing will require a significant degree of fracturing to enhance permeability and corresponding gas recovery in untested cells.

Given that historical exploration for continuous gas accumulations within the Lance–Fort Union CTPS is limited, it is unlikely that production results to date are entirely representative of the future gas potential. Anticipating the range of estimated ultimate recoveries (EURs) for untested cells in the AU (Appendix A), based on EUR distributions from 15

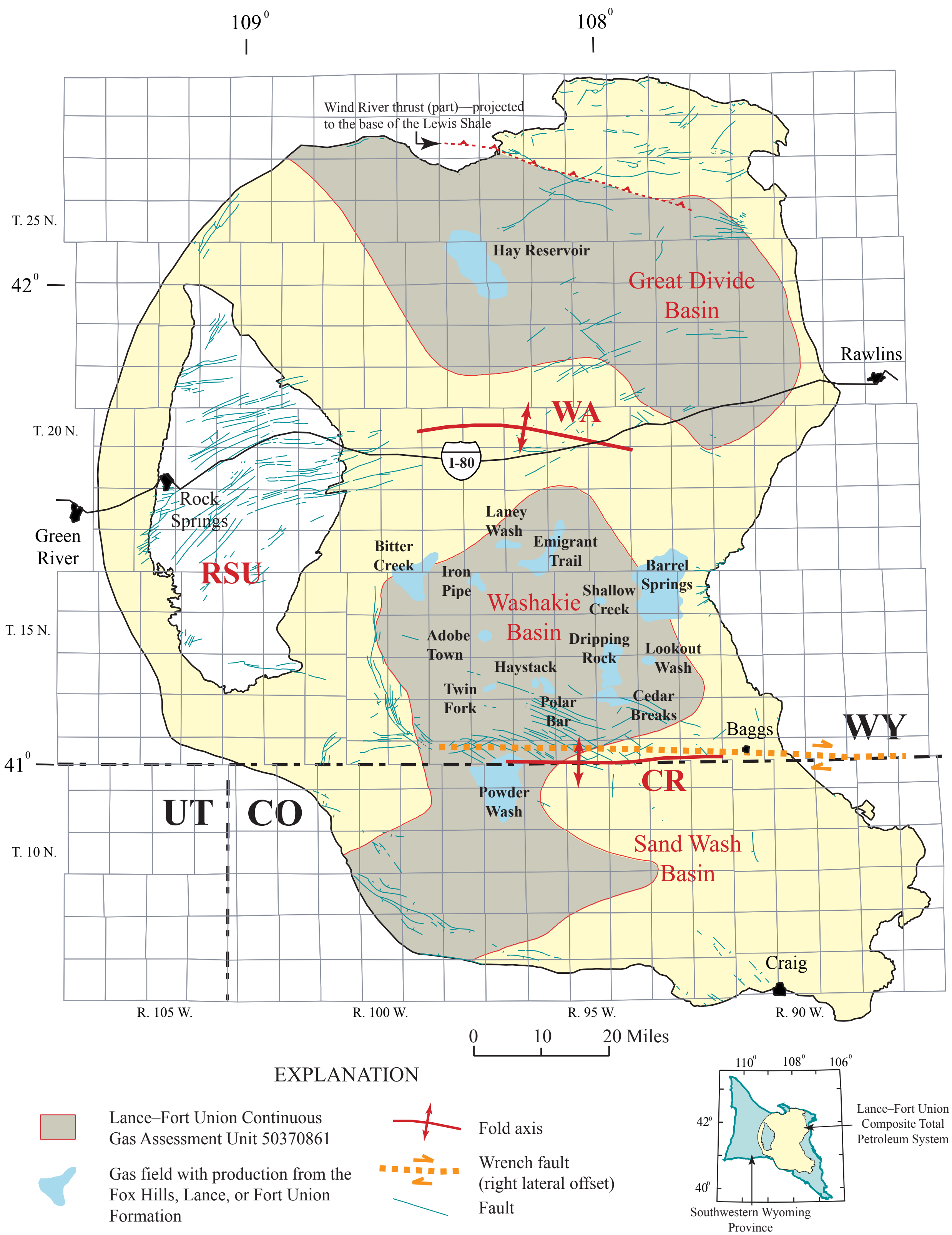

Figure 12. Boundary and extent of the Lance–Fort Union Continuous Gas Assessment Unit (50370861) and distribution of gas fields including wells that produce gas from the assessment unit in the Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Field boundaries are generalized and do not accurately reflect field extent. CR, Cherokee ridge; WA, Wamsutter arch; RSU, Rock Springs uplift.

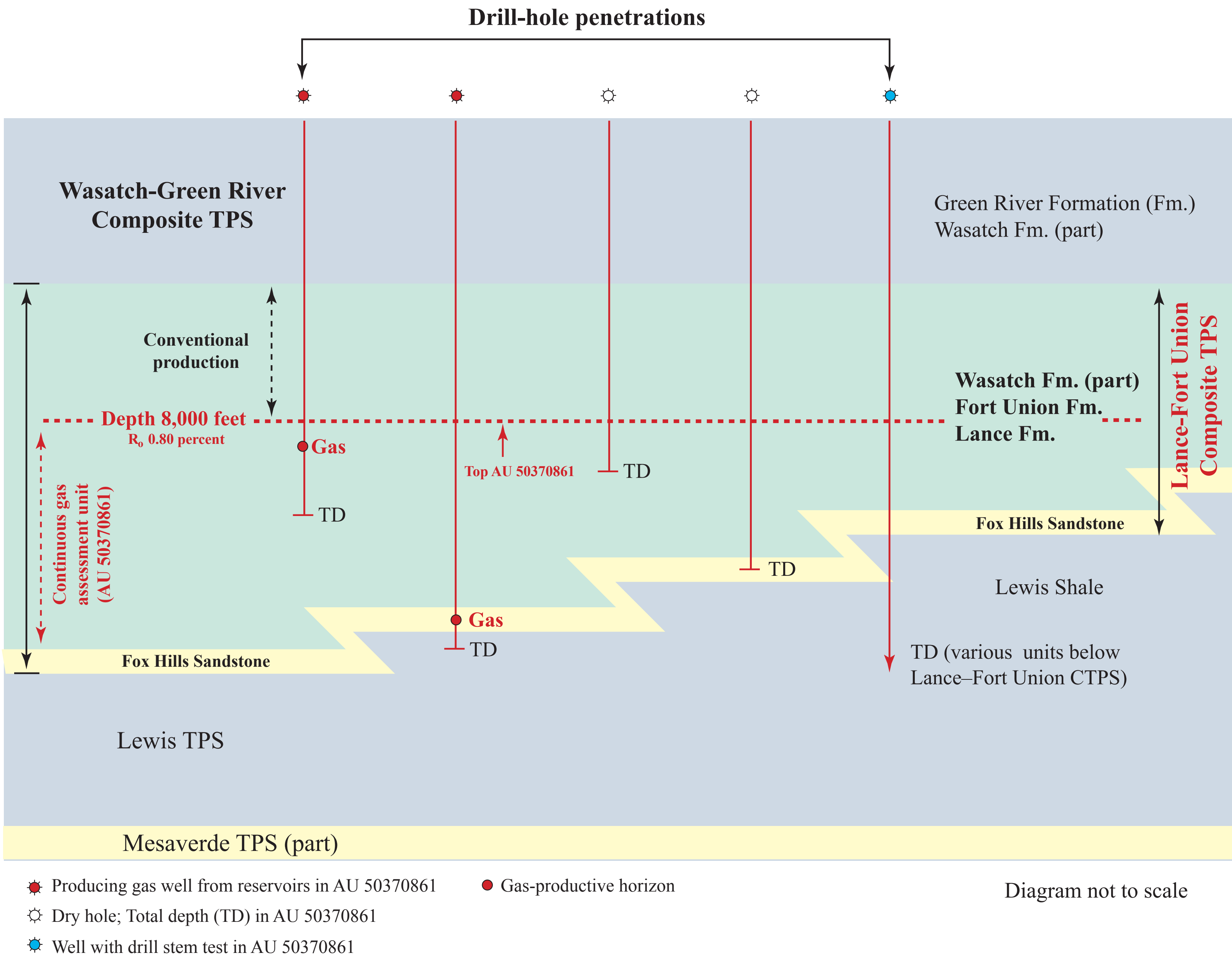

Figure 13. Schematic diagram showing criteria used to determine the number of evaluated (tested) cells within the Lance–Fort Union Continuous Gas Assessment Unit (50370861), Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Tested cells for the assessment unit include gas wells producing from CTPS units below an 8,000-ft depth cutoff, dry holes that terminated in CTPS units below the 8,000-ft depth cutoff, and wells with reported drill stem tests within CTPS units below the 8,000-ft depth cutoff.

producing wells alone (fig. 14), is probably not meaningful. For this reason, comparisons were again made with continuous gas analogs in another part of the Southwestern Wyoming Province (Pinedale field; Finn and others, Chapter 10, this volume), and in the Uinta and Piceance Basins (Johnson and Roberts, 2003). A minimum EUR of 0.02 BCFG was applied to untested cells in the Lance–Fort Union Continuous Gas AU (Appendix A). This minimum value is identical to minimum EURs established for analog gas-assessment units in the Uinta and Piceance Basins (Johnson and Roberts, 2003) and reflects our estimated minimum recovery for a well (cell) to be considered successful. Determination of a median EUR for untested cells also drew heavily from comparison to analog areas. The median EUR derived from the 15 producing wells identified in the Lance–Fort Union Continuous Gas assessment unit is about 0.08 BCFG (fig. 14). By comparison, median EURs calculated for comparative field areas range from about 0.3 BCFG (Pinedale field) to a high of about 1.7 BCFG in Jonah field (fig. 15), where advances in completion and reservoir stimulation techniques have greatly enhanced gas recovery (Finch and others, 1997). Overall median EURs for continuous gas AUs in the Uinta and Piceance Basins are 0.7 and 0.5 BCFG, respectively, and the median EUR for the most recent one-third of the producing wells in those assessment units is about 0.7 BCFG (Johnson and Roberts, 2003). In this analysis, a median EUR of 0.8 BCFG was applied to untested cells within the Lance–Fort Union Continuous Gas AU (Appendix A). This value is slightly higher than EURs for recent wells in Uinta and Piceance Basin analogs, reflecting optimism in regard to improved recovery techniques in low-permeability, fluvial sandstone reservoirs. Although median well recoveries at Jonah are significantly higher than 0.8 BCFG (fig. 15), median EURs for the majority of untested cells in the Lance–Fort Union Continuous Gas AU are not anticipated to reach the high production levels seen at Jonah field. Maximum EURs calculated for the analog areas range from about 4 BCFG (Pinedale field and Piceance Basin) to more than 10 BCFG in the Uinta Basin. Given that exploration in the Lance–Fort Union Continuous Gas AU is so limited, and again, because production technologies related to fluvial

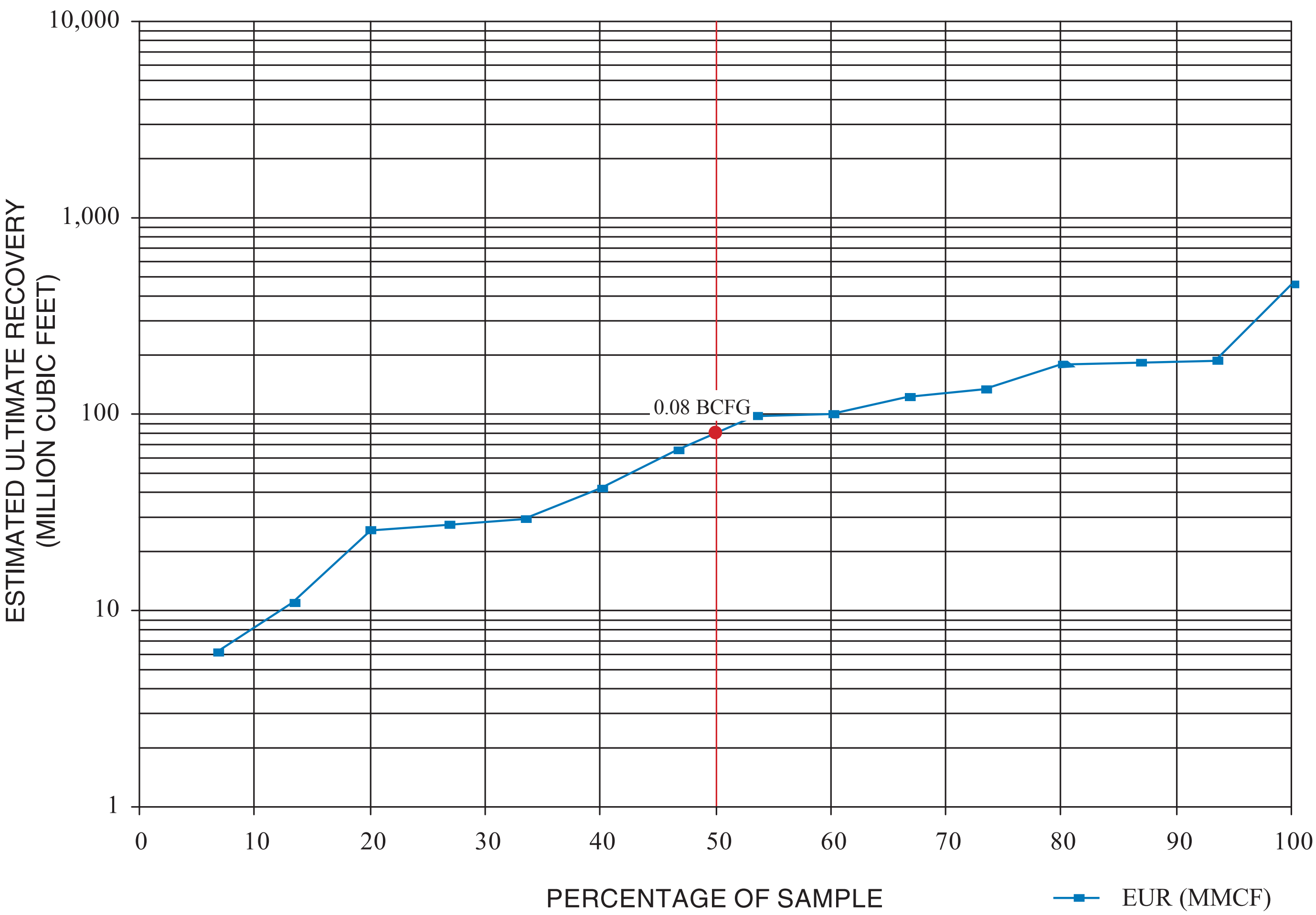

Figure 14. Graph showing the distribution of estimated ultimate recoveries (EURs) based on 15 gas wells within the Lance–Fort Union Continuous Gas Assessment Unit (50370861), Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas are represented by the graph.

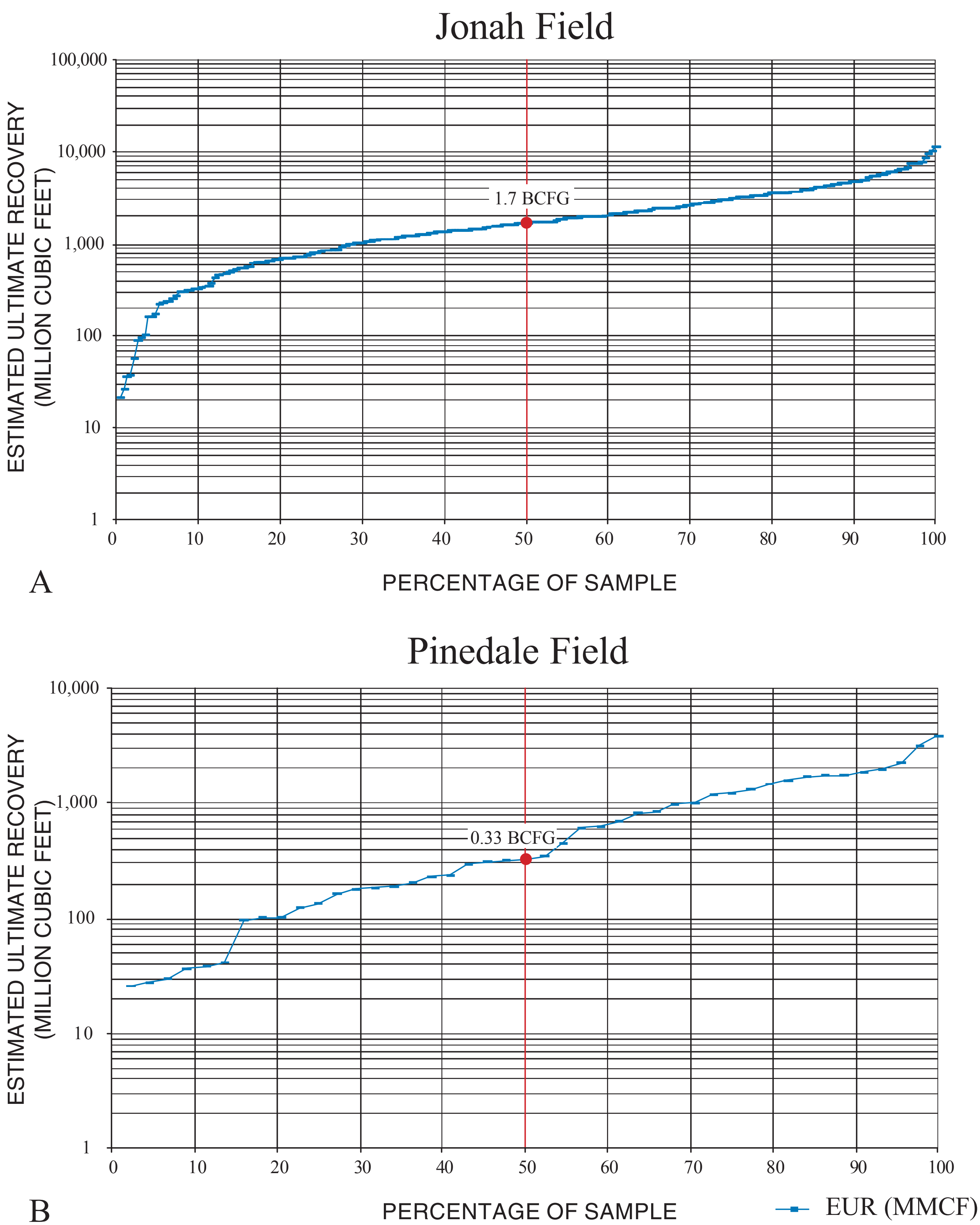

Figure 15. Graphs showing the distribution of estimated ultimate recoveries (EURs) for gas wells producing from the Lance and Fort Union Formations in (A) the Jonah field and (B) the Pinedale field in the Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Location of Jonah and Pinedale fields is shown in figure 2. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas are represented by the graph.

reservoirs have improved, a maximum EUR of 10 BCFG was applied to untested cells, similar to EURs observed in larger gas wells in the Uinta Basin (Greater Natural Buttes field).

Primary geologic factors that could influence future gas production potential within untested areas of the AU include the presence (or absence) of faults and natural fracture systems, and the distribution of mature source rocks (R_o greater than 0.8 percent) within both the Lance and Fort Union Formations. Because of the generally low permeabilities (less than 1 mD) that have been observed or are anticipated for many reservoirs in the AU (for example, see Scotia Group, 1993), naturally fractured sandstone beds might be critical for the development of productive sweet spots. It should be noted, however, that a detrimental aspect of fracture systems is the possible enhancement of permeability to water as well as gas (Krystinik and Lorenz, 2000; Evans and others, 2000). Significant volumes of water introduced through fractures could adversely affect gas production potential in some areas. Faults and fractures, however, might also provide conduits for gas migration through thick, relatively impermeable mudrock layers common in CTPS units, thus charging reservoirs over a thicker stratigraphic interval. Similarly, a thicker portion of the stratigraphic column might also be gas charged in areas where both Lance and Fort Union source rocks are thermally mature with respect to gas generation (R_o greater than 0.8 percent). Where source rocks exceed an R_o of 1.1 percent, reservoirs have a greater potential to be gas saturated.

The estimate of the minimum percentage of the untested AU area that has the potential for additions to reserves within the next few decades is 5 percent (Appendix A). This minimum estimate takes into account the very marginal success of gas production to date and assumes that only limited areas surrounding current producing wells or areas that contain well-developed fault and fracture systems associated with major Laramide structures will be productive. However, because this estimate focuses on areas where geologic conditions seem most optimal, a maximum potential success ratio of 80 percent was applied to the analysis of the minimum area. The estimated median area with potential additions to reserves is 25 percent. This estimate expands on the minimum estimate by including areas where source-rock thermal maturity in the Fort Union Formation exceeds an R_o of 0.8 percent and where thermal maturity in potential Lance source rocks is at or near 1.10 percent R_o. Because of the larger area and corresponding uncertainty as to the geologic conditions, a reduced success ratio of 70 percent was applied. The estimated maximum percentage of the untested AU area with potential reserve additions in the next 30 years is 40 percent. This estimate incorporates the minimum and median areas and expands on those estimates by including all areas where basal Lance Formation thermal maturity exceeds 1.10 percent (fig. 6) and areas where the depth to the base of the Lance Formation is within 8,000–12,000 ft of the ground surface (fig. 4). This depth range is considered deep enough (in most cases) to penetrate gas-bearing, overpressured strata (Law, 1984; Law and others, 1989) but not so deep as to penetrate the extremely tight reservoirs anticipated at greater depths. An anticipated minimum success ratio of 60 percent was applied to this estimate, based on the lack of geologic data in much of the area and the uncertainty that strata at shallower depths (8,000–10,000 ft) will be gas bearing and overpressured in all cases.

50370881: Lance Coalbed Gas Assessment Unit (hypothetical)

The Lance Coalbed Gas Assessment Unit (fig. 16) includes areas where coal beds in the basal 300–500 ft of the Lance Formation are interpreted to be at depths of 6,000 ft or less. The location of the 6,000-ft cutoff line is based on depth projections to the top of the Lewis Shale. The AU includes about 2,351,000 acres (3,670 mi^2), and variability in the AU area (minimum-median-maximum extent; Appendix B) results from limited drill-hole data for structural interpretations on top of the Lewis Shale in some areas, and uncertainty as to the presence of the Lance Formation in areas near the Rock Springs uplift (fig. 16). This AU is considered hypothetical because there has been no recorded production of coalbed gas from the Lance Formation.

Cumulative coal thickness in the Lance typically is less than 30–40 ft, with minimum values of less than 10 ft and a maximum reported total coal thickness of 85 ft; reported thickness for individual coal beds within the AU ranges from less than 1 ft to as much as 13 ft (Law, 1996). Thermal maturity (R_o) values in the AU range from about 0.4 percent (Law, 1996) to 0.8 percent in very limited areas of the southwestern Great Divide Basin. The apparent rank of Lance Formation coal on the southeast flank of the Rock Springs uplift is subbituminous B, and the coal beds in this area typically have ash yields averaging about 5 percent, total sulfur contents averaging about 0.7 percent, and average moisture contents of about 20 percent (Keystone Coal Industry Manual, 1999).

Because no coalbed-gas production or test data specific to the Lance Formation are available, coalbed-gas wells producing from subbituminous coal in the Fort Union Formation in the Powder River Basin were used as analogs for estimating the cell size and total recovery per cell for untested cells in the Lance Coalbed Gas Assessment Unit (Appendix B). Reported gas contents for Fort Union Formation coal in the Powder River Basin can vary from 6 to more than 75 standard cubic ft/ton (scf/ton) and are commonly in the range of 20–40 scf/ton (for example, see Stricker and others, 2000; Boreck and Weaver, 1984). It is assumed in this study that, because coal beds in the Lance and Fort Union Formations are of similar rank (subbituminous), gas contents might also be similar. Much of the Powder River Basin coalbed-gas production comes from the Wyodak coal bed, which exceeds 100 ft in thickness in many areas. Because of the exceptional thickness of the Wyodak bed compared to typical Lance Formation coal bed thickness, Powder River Basin analogs used for EUR estimates were restricted to gas wells producing from the

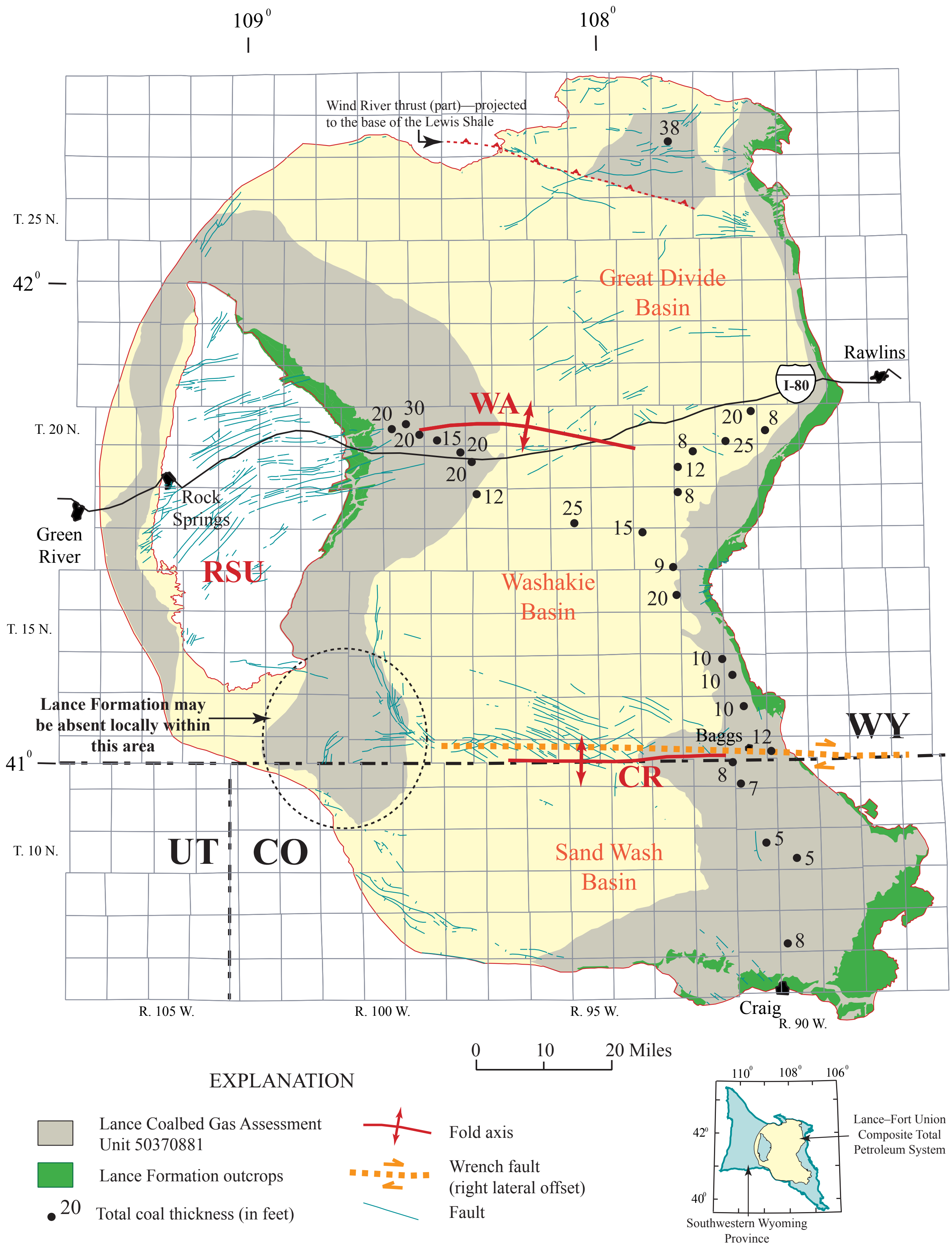

Figure 16. Map showing the boundary and extent of the Lance Coalbed Gas Assessment Unit (50370881), and total coal thickness estimates for the lower part of the Lance Formation from selected oil and gas wells, Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Lance Formation outcrops from Green (1992) and Green and Drouillard (1994). CR, Cherokee ridge; WA, Wamsutter arch; RSU, Rock Springs uplift.

Anderson or Canyon coal beds, which commonly range from 20 to 30 ft in thickness.

Depending on coal bed continuity, cleat development, and natural fracturing, effective reservoir drainage areas for individual coalbed gas wells can be highly variable. The determination of gas drainage areas and the selection of cell sizes used for the Lance Coalbed Gas AU drew directly from cell sizes applied to coalbed-gas assessment units in the Powder River Basin. Based on those data, areas per cell of untested cells having potential for additions to reserves are estimated at a minimum of 40 acres, a median of 80 acres, and a maximum of 140 acres (Appendix B). A 40-acre cell size was used at the minimum because of strong evidence for interference between coalbed gas wells producing at 20-acre spacing in the Powder River Basin, and although some interference has also been observed at 40-acre spacing, its occurrence is reduced (Romeo Flores, U.S. Geological Survey, personal commun., 2003). The 80-acre cell size applied to the median estimate is considered optimal in regard to gas volume and recovery, dewatering considerations, and reduction (or omission) of interference between adjacent wells. The maximum estimate of 140 acres accounts for increased drainage areas in exceptionally continuous and permeable coal beds.

Although no direct correlation has been made between coal thickness, gas content, and enhanced production, greater coal volumes associated with thick coal beds should result in a greater volume of coalbed-gas per unit area of land (for example, see Choate and others, 1984). Thus, given the low volume of total coal in the Lance Formation relative to the Fort Union Formation in the Powder River Basin, volumes of gas per unit of acreage and corresponding ultimate recovery for individual wells might be significantly less in the Lance Coalbed Gas AU than in Powder River Basin analogs, assuming all other factors (gas content, water content, permeability, and so forth) are equal. A minimum EUR of 0.02 BCFG was applied to untested cells in the assessment unit (Appendix B). This value is identical to minimum values applied in Powder River Basin analogs, and is the value generally considered to represent the minimum gas recovery required for a successful well. A median EUR of 0.15 BCFG was applied to untested cells in the Lance Coalbed Gas AU. Analog gas wells producing from the Anderson and Canyon coal beds in the Powder River Basin had median EURs ranging from 0.15 to 0.20 BCFG, respectively (Troy Cook, U.S. Geological Survey, oral commun., 2002). Because of the differences in coal thickness and volume between the Lance Formation in the AU and the Fort Union Formation in analog coalbed-gas wells, the lower of the median values was applied. The maximum EUR for untested cells is estimated at 1 BCFG. By comparison, maximum EURs in Powder River Basin wells were about 1.25 BCFG for the Anderson coal bed, and 1.5 BCFG for the Canyon coal bed (Troy Cook, oral commun., 2002). Again, because of the anticipated differences in gas volume due to the lesser coal volume, a maximum EUR of 1.0 BCFG, which is less than both analog EURs, was applied to untested cells in the Lance Coalbed Gas AU.

Estimates for the percentage of the untested AU area with the potential for additions to reserves are a minimum of 1 percent, a median of 3 percent, and a maximum of 7 percent (Appendix B). The minimum value represents a small potential related to thicker total coal accumulations (greater than 30 ft) in areas such as the small, structurally complex area north of the projected position of the Wind River thrust (fig. 16). The median estimate includes the minimum area coupled with potential areas on Cherokee ridge where Lance coalbed gas could be considered a "behind-pipe" resource in existing conventional gas fields. The maximum area factors in the potential for Lance coalbed gas near existing coal mines along the eastern flank of the Rock Springs uplift, where total coal accumulations are from 15 to 30 ft, and structure associated with the Wamsutter arch could aid in gas accumulation.

50370882: Fort Union Coalbed Gas Assessment Unit (hypothetical)

The Fort Union Coalbed Gas Assessment Unit (fig. 17) includes areas where coal beds in the basal 1,000 ft of the Fort Union Formation are interpreted to be at depths of 6,000 ft or less. The location of the 6,000-ft cutoff line is based on depth projections to the top of the unnamed Cretaceous-Tertiary sandstone unit of Hettinger and others (1991) or the top of the Lance Formation where the unnamed unit is not present or identified. Areas where the Fort Union Formation is present along the eastern margin of the Great Divide Basin and north of the projected Wind River thrust (fig. 17) are excluded from the AU because of steep dips and(or) the diminished presence of coal due to erosion and lateral facies changes (for example, see Honey and Roberts, 1994). The AU includes a mean estimated area of about 3,047,000 acres (4,760 mi^2), and variability in the AU area (minimum-median-maximum extent; Appendix C) results from limited drill-hole data to determine depth to the top of the Lance Formation in some areas. Gas has been documented in Fort Union Formation coal beds in the CTPS, with measured gas contents generally less than 100 standard cubic feet per ton (scf/ton) (Tyler and others, 1995). One well that spudded in the Fort Union Formation on the east flank of the Rock Springs uplift (T. 19 N., R. 99 W.) recorded gas at a depth of 240 ft (McCord, 1984). However, this AU is considered hypothetical because there is no record of sustained production of coalbed gas from the Fort Union Formation (IHS Energy Group, 2001).

Fort Union coal bed thickness within the AU ranges from less than 1 ft to as much as 50 ft, and continuous coal beds or zones are present within 1,000–1,200 ft above the base of the formation (lower coal-bearing unit; Tyler and others, 1995). Cumulative coal thickness in this lower interval exceeds 80 ft in areas of the AU along Cherokee ridge and the Wamsutter arch (fig. 17) and may exceed 100 ft locally (Tyler and McMurry, 1993; Tyler and others, 1995). Additional coal beds are present in the Cherokee coal zone and equivalent strata in the upper 200–500 ft of the formation (upper shaly unit; Beau-

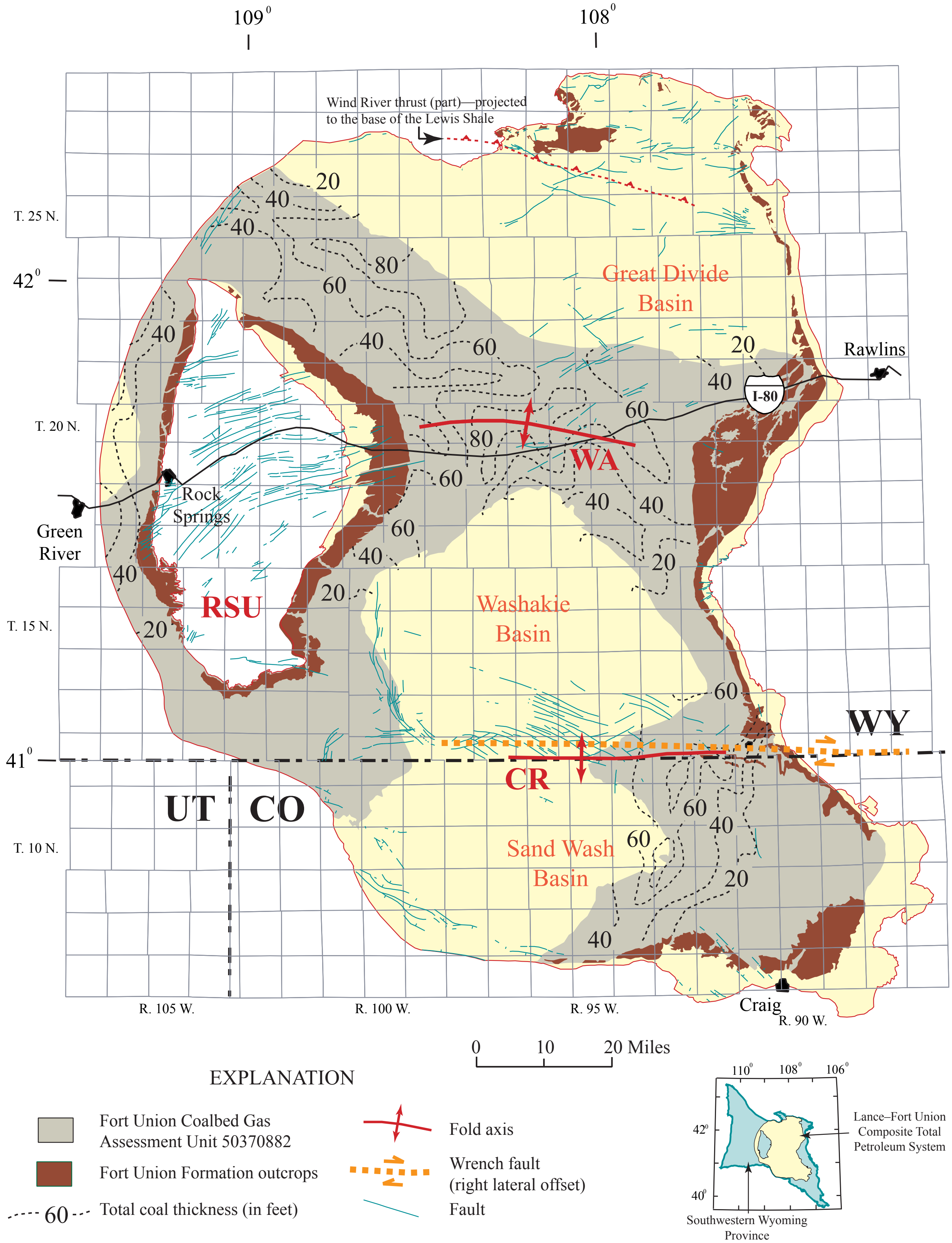

Figure 17. Boundary and extent of the Fort Union Coalbed Gas Assessment Unit (50370882) and total coal thickness estimates for the lower part of the Fort Union Formation within the assessment unit, Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Total coal thickness modified from Tyler and others (1995); contour interval 20 feet. Fort Union Formation outcrops from Green (1992) and Green and Drouillard (1994). CR, Cherokee ridge; WA, Wamsutter arch; RSU, Rock Springs uplift.

mont, 1979; Tyler and others, 1995; unnamed upper Paleocene unit of Hettinger and others, 1991); coal beds in this interval tend to be more lenticular than coal beds in the lower coal-bearing interval (for example, see Hettinger and others, 1991; Tyler and McMurry, 1993). Thermal maturity (R_o) values for coal in the AU range from about 0.40 percent to about 0.65 percent (Law, 1996); thermal maturity values exceeding an R_o of 0.60 percent are present along the crest and flanks of the Wamsutter arch and in the east-central part of the Sand Wash Basin. The apparent rank of Fort Union coal is subbituminous, and as-received analyses of coal beds in the lower coal-bearing interval on the east flank of the Rock Springs uplift indicate moisture values averaging 17.69 percent, ash yields averaging 8.48 percent, total sulfur averages of 0.41 percent, and average heating values of 9,728 Btu/lb (Glass, 1981, after Root and others, 1973). As-received analyses of the upper and lower Cherokee coal beds in the Cherokee coal zone near the top of the Fort Union Formation indicate moisture ranging from 15 to 25 percent, ash yields ranging from 10 to 25 percent, total sulfur ranging from 0.5 to 5.0 percent, and heating values ranging from 5,000 to 9,000 Btu/lb (Glass, 1981, after Smith and others, 1972).

Coalbed gas wells producing from subbituminous coal in the Fort Union Formation in the Powder River Basin were used as analogs for estimating the cell size and total recovery per cell for untested cells in this coalbed gas AU (Appendix C). As previously described for the Lance Coalbed Gas Assessment Unit, Anderson and Canyon coalbed analogs from the Powder River Basin were used for EUR analysis. In general, coal bed thickness in the Fort Union Formation in this AU is comparable to thickness reported for the Anderson and Canyon coal beds. For example, Tyler and others indicate that thicker Fort Union Formation coal beds in the Sand Wash Basin range from 20 to 50 ft thick, and are as thick as 40 ft in the Great Divide and Washakie Basins. Glass (1981) reports that the Anderson coal bed in the Powder River Basin varies from 10 to 50 ft in thickness, and the Canyon coal bed ranges from 11 to 65 ft in thickness. Fort Union Formation coalbed-gas contents in the Powder River Basin typically range from less than 10 to more than 75 standard cubic ft/ton (scf/ton) and are commonly in the range of 20–40 scf/ton (for example, see Stricker and others, 2000; Boreck and Weaver, 1984). By comparison, gas contents for Fort Union Formation coal (126 samples) from eight wells in the Sand Wash Basin vary from about 9 to more than 300 cubic ft/ton (cf/ton), and average about 63 cf/ton (Scott, 1993). Given these similarities, it is assumed that potential EURs in the AU might be comparable to Anderson and Canyon coalbed-gas well analogs.

Based on drainage area criteria applied in the Powder River Basin (Romeo Flores, U.S. Geological Survey, oral commun., 2003), areas per cell of untested cells in this AU having potential for additions to reserves are estimated at a minimum of 40 acres, a median of 80 acres, and a maximum of 140 acres (Appendix C). A 40-acre cell size was used at the minimum because of the potential for interference between wells producing at a closer spacing. An 80-acre cell size (median estimate) is considered optimal in regard to gas volume and recovery, dewatering considerations, and reduction (or omission) of interference between adjacent wells. The maximum of 140 acres considers the potential for increased drainage areas in exceptionally continuous and permeable coal reservoirs.

Because coal bed thickness, continuity, and coalbed-gas contents in this AU compare favorably with Anderson and Canyon analogs in the Powder River Basin, it is postulated that estimated ultimate recoveries for untested cells (Appendix C) in the Fort Union Coalbed Gas AU could closely follow EURs derived from Powder River Basin analog production data. A minimum EUR of 0.02 BCFG was applied to untested cells in this AU. This value is generally considered representative of the minimum gas recovery required for a successful well. A median EUR of 0.20 BCFG was applied to untested cells in this AU, which is directly correlative to median EURs estimated from Canyon coalbed gas production data (Troy Cook, U.S. Geological Survey, oral commun., 2002). Similarly, the maximum EUR of 1.5 BCFG is based directly on EURs estimated from Canyon coalbed production.

Estimates for the percentage of the untested AU area with the potential for additions to reserves are a minimum of 3 percent, a median of 10 percent, and a maximum of 20 percent (Appendix C). The minimum value represents a small potential related to thicker total coal accumulation along Cherokee ridge (fig. 17), where the gassy nature of Fort Union coal is documented (Parker and Bortz, 2001) and where existing structural closure could enhance gas entrapment. The median estimate includes the minimum area coupled with additional potential areas on crest of the Wamsutter arch, where total coal accumulations are thick and associated with structure. In addition, established fields along both arches provide a gas-production infrastructure, which could enable development of Fort Union coal bed gas as a “behind pipe” resource. The maximum area includes the minimum and median areas, plus areas on the flanks of structural arches where total coal thickness exceeds 40–60 ft and where additional gas fields include the potential for recompletion in Fort Union coalbed reservoirs.

50370801: Lance–Fort Union Conventional Oil and Gas Assessment Unit

The Lance–Fort Union Conventional Oil and Gas Assessment Unit (fig. 18) represents an area in which hydrocarbons derived from Lance and Fort Union Formation source rocks are produced from or have the potential to be produced from relatively shallow (less than 7,000–8,000 ft), conventional accumulations in discrete structural, stratigraphic, or combined structural/stratigraphic traps with downdip, gas-water contacts. Accumulations within this AU are interpreted to have formed from the vertical or up-dip migration of hydrocarbons from thermally mature, coal and organic-rich source rocks in the deep portions of the Washakie, Sand Wash, and Great Divide Basins. Because the potential exists for hydrocarbons to migrate into reservoirs throughout the entire petroleum

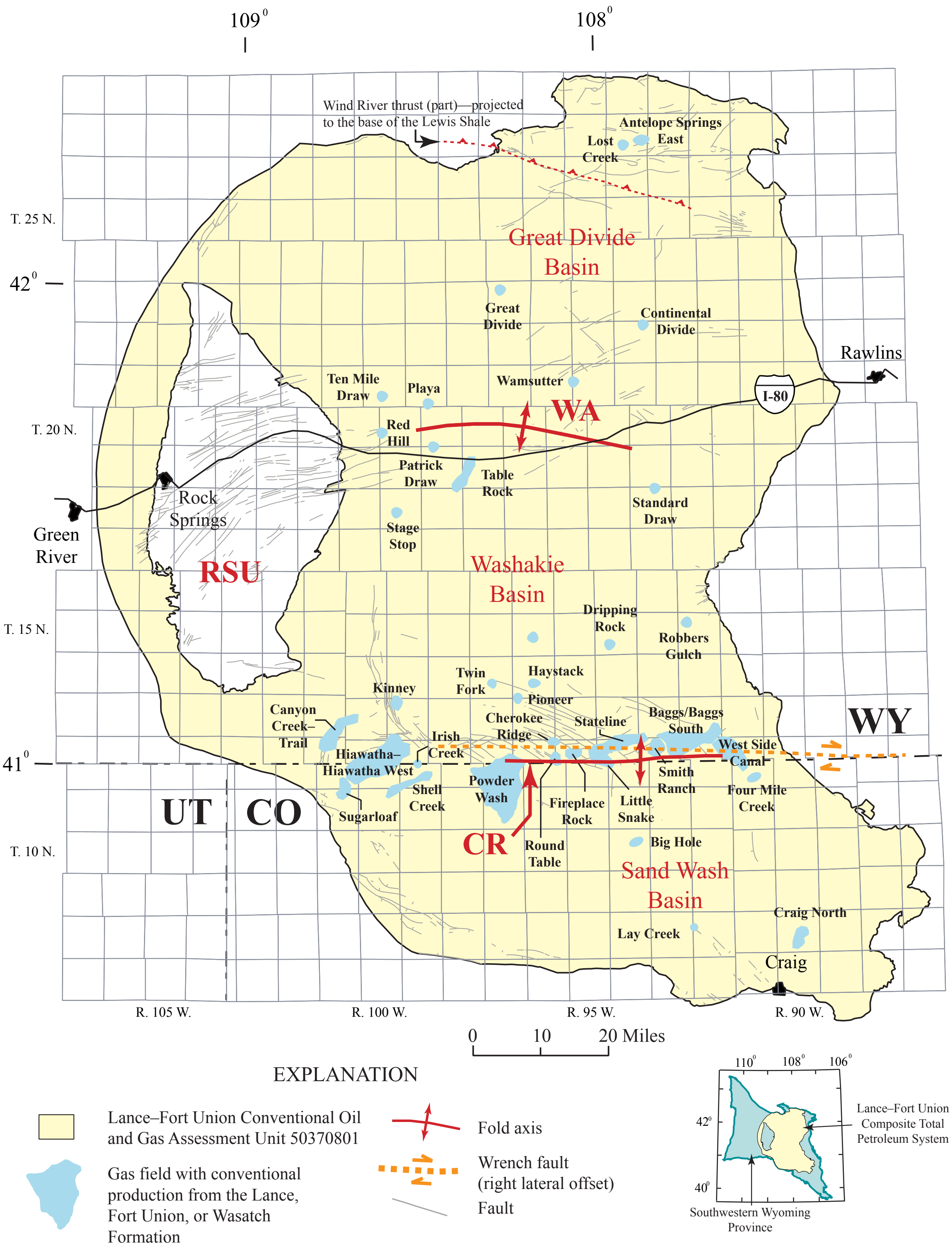

Figure 18. Boundary and extent of the Lance–Fort Union Conventional Oil and Gas Assessment Unit (50370801), and location of fields that include wells producing gas and(or) limited oil from conventional reservoirs within the assessment unit, Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Field boundaries are generalized and do not accurately reflect field extent. CR, Cherokee ridge; WA, Wamsutter arch; RSU, Rock Springs uplift.

system, the Lance–Fort Union Conventional Oil and Gas Assessment Unit boundary is coincident with the boundary of the Lance–Fort Union CTPS (fig. 2). This AU overlaps the Lance–Fort Union Continuous Gas Assessment Unit, where thermal maturities exceed an R_o of 0.8 percent and extends laterally to basin margin areas where thermal maturities are less than an R_o of 0.6 percent. Because this AU overlies the Lance–Fort Union Continuous Gas AU, the 8,000-ft depth cutoff used to define the top of the continuous accumulation (with some exceptions) also demarks the base of this conventional AU. Volumetrically, gas is the primary hydrocarbon produced from the AU, and although some oil is produced, no oil production in any single field (grown) exceeds 0.5 million barrels of oil equivalent (MMBOE). For this reason, only undiscovered gas accumulations were evaluated.

Within the AU there are some 368 wells with total depths less than 8,000 ft that are producing hydrocarbons from CTPS reservoirs; of this total, 288 are classified as gas wells (IHS Energy Group, 2001). Gas reservoirs are primarily fluvial sandstone beds in the Lance, Fort Union, and Wasatch Formations, and shoreface/marginal marine sandstone reservoirs in the Fox Hills Sandstone. Most of the gas production within the AU comes from fields along Cherokee ridge (CR) (fig. 18), where en-echelon, anticlinal folds that formed during Laramide structural development of the arch provided traps for hydrocarbon accumulation. Structural closure in individual folds on the arch can be several hundreds of feet at depth in more productive fields (for example, see Biggs and Espach, 1960; Millison, 1965; Collins, 1971; Parker and Bortz, 2001). Faults dissect many of these folds, offsetting Cretaceous and Tertiary strata in the subsurface and also providing potential hydrocarbon traps where faults juxtapose porous units with adjacent impermeable lithologies, or where faults provide up-plunge and updip closure in folds (Bader, 1987). Stratigraphic traps also formed where lenticular sandstone beds pinch out in impermeable shale and mudstone that commonly surround these sandstone bodies. In many or most of the conventional fields on Cherokee ridge, the combination of structural and stratigraphic traps is considered as the key factor for significant hydrocarbon accumulation. Reservoir sandstone porosities along Cherokee ridge range from 12 to 39 percent and average about 22 percent; permeability ranges from less than 0.50 to more than 1,500 millidarcies (mD). Average pay thickness is about 20–25 ft, although pay thickness exceeding 200 ft can result with production from multiple pay zones (Cardinal and Hovis, 1979; Farmer, 1979; Lehman, 1979; McCutcheon, T.J., 1992; Cardinal, 1992a–e). Limited additional production within the AU comes from fields along the western part of the Wamsutter arch and from scattered fields overlying deeper basinal areas.

Six gas fields within the AU exceed the minimum field size (grown) of 3 BCFG. These fields include Baggs South, West Side Canal, and Powder Wash fields on Cherokee ridge, and Canyon Creek-Trail, Hiawatha-Hiawatha West, and Kinney fields on the southeast side of the Rock Springs uplift (fig. 18). Average reservoir depths in these fields typically range from 1,000 to 5,500 ft (NRG Associates, 2001) although perforated intervals in Fort Union reservoirs in Powder Wash field are as deep as 8,200 ft (IHS Energy Group, 2001). However, Powder Wash field also lies within the Lance–Fort Union Continuous Gas AU (50370861), and for this reason, production at depths of about 8,000 ft or more in this field is considered to be part of the underlying continuous accumulation. Based on analysis of these six conventional gas fields, grown field size within the AU has decreased markedly in the more recently discovered fields (fig. 19), and this fact influenced estimates of the number and size of undiscovered accumulations (Appendix D). The minimum estimate of two undiscovered gas accumulations greater than the minimum size (3 BCFG) assumes that faulted, closed anticlinal structures are key to gas accumulation within the AU, and that the mature level exploration targeting these structures along Cherokee ridge and the Wamsutter arch has essentially identified most of those gas accumulations. No new accumulations greater than the minimum have been discovered in more than 20 years. The median estimate of 30 undiscovered gas accumulations assumes an additional potential for stratigraphic or combined structural/stratigraphic traps in fault-bounded or fractured areas flanking Laramide arches or proximal to bounding uplifts surrounding the AU. The maximum of 75 undiscovered gas accumulations greater than 3 BCFG combines minimum and median estimates, coupled with additional potential in largely unexplored areas away from structural arches, where stratigraphic traps might form in abundant amalgamated and lenticular fluvial sandstone units that are prevalent within the Lance, Fort Union, and Wasatch Formations. Estimates of undiscovered gas field sizes (grown) above the minimum (3 BCFG) are 7 BCFG at the median and 25 BCFG at the maximum (Appendix D). These estimates are strongly influenced by the overall trend of decreasing field sizes since the earliest (pre-1950) field discoveries and the fact that the two most recently discovered fields have grown sizes ranging from about 5 BCFG to just under 20 BCFG (fig. 19). The estimated number of undiscovered gas fields exhibits a wide range of uncertainty and proposes a significant increase in the number of fields relative to what has been discovered to date; however, the overall size of the undiscovered fields is anticipated to be rather small (3–25 BCFG).

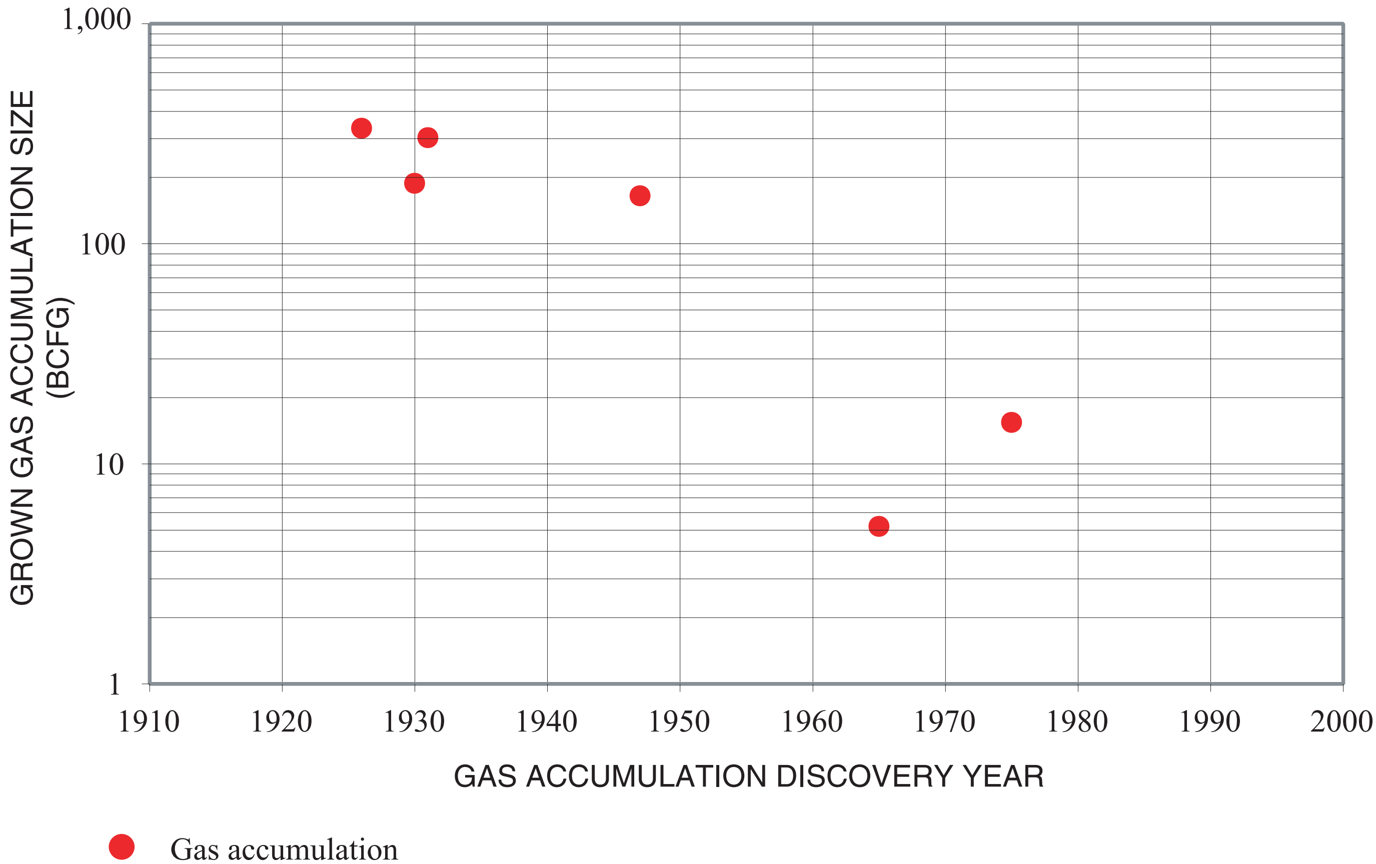

Figure 19. Size distribution (grown) of conventional gas accumulations by discovery year for selected gas fields within the Lance–Fort Union Conventional Oil and Gas Assessment Unit (50370801), Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Only fields with grown size exceeding 3 billion cubic feet of gas (3 BCFG) are represented on the graph.

Assessment of Undiscovered Resources—Summary of Results

Tabulated estimates of undiscovered gas and natural gas liquid (NGL) resources for assessment units in the Lance–Fort Union CTPS are listed in table 1. Oil resources associated with gas accumulations (for example, Powder Wash field) are included in NGL estimates.

In summary, the total mean estimate of undiscovered gas resources in the Lance–Fort Union Composite Total Petroleum System is about 8.9 trillion cubic feet (TCF). Of this total, a mean of about 7.6 TCF is included in the Lance–Fort Union Continuous Gas Assessment Unit (50370861), a mean of 0.17 TCF is estimated for the Lance Coalbed Gas Assessment Unit (50370881), and a mean of about 0.94 TCF is estimated for the Fort Union Coalbed Gas Assessment Unit (50370882). An additional mean estimate of 0.25 TCF of undiscovered gas is included in the Lance-Fort Union Conventional Oil and Gas Assessment Unit (50370801). Undiscovered natural gas resources in the Lance–Fort Union CTPS represent about 10 percent of the mean estimated total of 84.6 TCF of gas in the Southwestern Wyoming Province of Wyoming, Colorado, and Utah.

Table 1. Estimated undiscoverd resources in the Lance–Fort Union Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah.

[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
Lance–Fort Union Composite TPS													
Lance–Fort Union Conventional Oil and Gas AU	*Gas*					75.00	229.20	465.90	245.60	0.70	2.20	5.00	2.50
Total conventional resources						**75.00**	**229.20**	**465.90**	**245.60**	**0.70**	**2.20**	**5.00**	**2.50**
Lance–Fort Union Continuous Gas AU	*Gas*					4,450.60	7,255.80	11,829.10	7,583.30	39.40	71.10	128.40	75.80
Lance Coalbed Gas AU	*CBG*					78.20	152.00	295.50	165.00	0.00	0.00	0.00	0.00
Fort Union Coalbed Gas AU	*CBG*					513.90	891.20	1,545.40	942.50	0.00	0.00	0.00	0.00
Total continuous resources						**5,042.70**	**8,299.00**	**13,670.00**	**8,690.80**	**39.40**	**71.10**	**128.40**	**75.80**
Total conventional and continuous resources						**5,117.70**	**8,528.20**	**14,135.90**	**8,936.40**	**40.10**	**73.30**	**133.40**	**78.30**

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Appendix A. Basic input data form for the Lance–Fort Union Continuous Gas Assessment Unit (50370861), Lance–Fort Union CTPS, Wyoming and Colorado. The complete data input form, including allocations of potential additions to reserves for land entities, is listed in Klett and Le (Chapter 28, this CD–ROM).

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

IDENTIFICATION INFORMATION

Assessment Geologist:…	S.B. Roberts	Date:	8/19/2002
Region:……………………	North America	Number:	5
Province:………………….	Southwestern Wyoming	Number:	5037
Total Petroleum System:.	Lance-Fort Union Composite	Number:	503708
Assessment Unit:……….	Lance-Fort Union Continuous Gas	Number:	50370861
Based on Data as of:……	IHS Energy Group, 2001, Wyoming Oil and Gas Conservation Commission		
Notes from Assessor…..	Analogs: Mesaverde-Lance-Fort Union Continuous Gas Assessment Unit without Jonah Field; Piceance Basin Continuous Gas, and Uinta Basin Continuous 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:………… 110
Number of tested cells with total recovery per cell > minimum: ……... 41
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 ____ 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 2,199,000 median 2,444,000 maximum 2,810,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres): (values are inherently variable)
calculated mean 87 minimum 20 median 80 maximum 200

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 99.4 median 99.6 maximum 99.8

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 5 median 25 maximum 40

Appendix A. Basic input data form for the Lance–Fort Union Continuous Gas Assessment Unit (50370861), Lance–Fort Union CTPS, Wyoming and Colorado. The complete data input form, including allocations of potential additions to reserves for land entities, is listed in Klett and Le (Chapter 28, this CD–ROM). —Continued.

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	0.8	10

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	10	15

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	1.50	20.00
CO_2 content (%)……………………………….…...	0.10	0.50	1.80
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)………………………………….	2,400	3,200	5,000
Depth (m) of water (if applicable)……………….			

Success ratios:	calculated mean	minimum	median	maximum
Future success ratio (%)........	70	60	70	80

Historical success ratio, tested cells (%)... 37

Appendix B. Basic input data form for the Lance Coalbed Gas Assessment Unit (50370881), Lance–Fort Union CTPS, Wyoming and Colorado. The complete data input form, including allocations of potential additions to reserves for land entities, is listed in Klett and Le (Chapter 28, this CD–ROM).

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

IDENTIFICATION INFORMATION

Assessment Geologist:…	S.B. Roberts	Date:	8/20/2002
Region:……………………	North America	Number:	5
Province:………………….	Southwestern Wyoming	Number:	5037
Total Petroleum System:.	Lance-Fort Union Composite	Number:	503708
Assessment Unit:……….	Lance Coalbed Gas	Number:	50370881
Based on Data as of:……			
Notes from Assessor…..	Analogs: Powder River Basin Coalbed Gas, Anderson/Canyon Beds, Laramie Coal (Denver Basin)		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo) Gas
What is the minimum total recovery per cell?… 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 0
Number of tested cells with total recovery per cell ≥ minimum: ……... 0
Established (>24 cells ≥ min.) ____ Frontier (1-24 cells) ____ Hypothetical (no cells) X
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st 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 2,045,000 median 2,351,000 maximum 2,657,000

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

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

4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum)
(uncertainty of a fixed value) minimum 1 median 3 maximum 7

Appendix B. Basic input data form for the Lance Coalbed Gas Assessment Unit (50370881), Lance–Fort Union CTPS, Wyoming and Colorado. The complete data input form, including allocations of potential additions to reserves for land entities, is listed in Klett and Le (Chapter 28, this CD–ROM).—Continued.

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	0.15	1

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

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

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

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)…………….…………			
Sulfur content of oil (%)…………………….....…			
Drilling depth (m) ……………...…………….……			
Depth (m) of water (if applicable)……………….			
Gas assessment unit:			
Inert-gas content (%)…………………….....…..	2.00	3.00	4.00
CO_2 content (%)……………………………..…..	3.00	5.00	8.00
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)………………………………….	150	1,000	1,800
Depth (m) of water (if applicable)……………….			

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

Appendix C. Basic input data form for the Fort Union Coalbed Gas Assessment Unit (50370882), Lance–Fort Union CTPS, Wyoming and Colorado. The complete data input form, including allocations of potential additions to reserves for land entities, is listed in Klett and Le (Chapter 28, this CD–ROM).

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

IDENTIFICATION INFORMATION

Assessment Geologist:…	S.B. Roberts	Date:	8/20/2002
Region:……………………	North America	Number:	5
Province:…………………	Southwestern Wyoming	Number:	5037
Total Petroleum System:.	Lance-Fort Union Composite	Number:	503708
Assessment Unit:……….	Fort Union Coalbed Gas	Number:	50370882
Based on Data as of:……			
Notes from Assessor…..	Analogs: Upper Fort Union Coalbed Gas in Powder River Basin, Anderson/Canyon Beds		

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:………… 3
Number of tested cells with total recovery per cell ≥ minimum: ……... 0
Established (>24 cells ≥ min.) ______ Frontier (1-24 cells) ______ Hypothetical (no cells) X
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st 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 2,743,000 median 3,047,000 maximum 3,352,000

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

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

4. Percentage of untested assessment-unit area that has potential for additions to reserves in next 30 years (%): (a necessary criterion is that total recovery per cell ≥ minimum)
(uncertainty of a fixed value) minimum 3 median 10 maximum 20

Appendix C. Basic input data form for the Fort Union Coalbed Gas Assessment Unit (50370882), Lance–Fort Union CTPS, Wyoming and Colorado. The complete data input form, including allocations of potential additions to reserves for land entities, is listed in Klett and Le (Chapter 28, this CD–ROM).

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 0.2 maximum 1.5

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 (%)………………………....…..	2.00	3.00	4.00
CO_2 content (%)……………………………….…..	3.00	5.00	8.00
Hydrogen-sulfide content (%)……………...…….	0.00	0.00	0.00
Drilling depth (m)………………………………….	150	1,000	1,800
Depth (m) of water (if applicable)……………….			

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

Historical success ratio, tested cells (%)... 0

Appendix D. Basic input data form for the Lance–Fort Union Conventional Oil and Gas Assessment Unit (50370801), Lance–Fort Union CTPS, Wyoming and Colorado. The complete data input form, including allocations of potential additions to reserves for land entities, is listed in Klett and Le (Chapter 28, this CD–ROM).

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

IDENTIFICATION INFORMATION

Assessment Geologist:……..	S.B. Roberts	Date:	8/20/2002
Region:………………………..	North America	Number:	5
Province:……………………….	Southwestern Wyoming	Number:	5037
Total Petroleum System:……	Lance-Fort Union Composite	Number:	503708
Assessment Unit:……………	Lance-Fort Union Conventional Oil and Gas	Number:	50370801
Based on Data as of:……….	NRG 2001 (data current through 1999), IHS Energy Group, 2001		
Notes from Assessor……….	NRG Reservoir Lower 48 growth function		

CHARACTERISTICS OF ASSESSMENT UNIT

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

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: 0 Gas: 6
Established (>13 accums.) ____ Frontier (1-13 accums.) X 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 302 2nd 3rd 15 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. (>0)	median no.	max no.
Oil Accumulations:…………………	0	0	0
Gas Accumulations:………………	2	30	75

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):…...…			
Gas in Gas Accumulations (bcfg):….….	3	7	25

Appendix D. Basic input data form for the Lance–Fort Union Conventional Oil and Gas Assessment Unit (50370801), Lance–Fort Union CTPS, Wyoming and Colorado. The complete data input form, including allocations of potential additions to reserves for land entities, is listed in Klett and Le (Chapter 28, this CD–ROM)—Continued.

Assessment Unit (name, no.)
Lance-Fort Union Conventional Oil and Gas, Assessment Unit 50370801

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

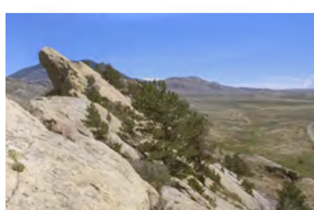
Oil Accumulations:	minimum	median	maximum
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			

Gas Accumulations:	minimum	median	maximum
Liquids/gas ratio (bliq/mmcfg)	5	10	15
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)			
Sulfur content of oil (%)			
Drilling Depth (m)			
Depth (m) of water (if applicable)			

Gas Accumulations:	minimum	median	maximum
Inert gas content (%)	0.1	1.5	20
CO_2 content (%)	0.1	0.5	1.8
Hydrogen-sulfide content (%)	0	0	0
Drilling Depth (m)	300	1,200	2,500
Depth (m) of water (if applicable)			



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