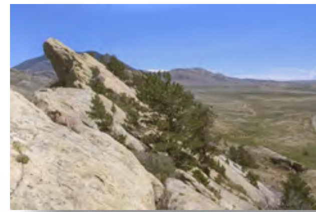
Chapter 12

Geologic Assessment of Undiscovered Petroleum Resources in the Wasatch–Green River Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah



Click here to return to
Volume Title Page

By Stephen B. Roberts

Chapter 12 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

U.S. Geological Survey Digital Data Series DDS–69–D

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Denver, Colorado: Version 1, 2005

For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Manuscript approved for publication May 10, 2005

ISBN= 0-607-99027-9

Contents

Figures

Table

Geologic Assessment of Undiscovered Petroleum Resources in the Wasatch–Green River Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah

By Stephen B. Roberts

Abstract

The Wasatch–Green River composite total petroleum system (CTPS) in the Southwestern Wyoming Province contains source rocks and potential hydrocarbon accumulations within Tertiary (Eocene) strata in the Wasatch and Green River Formations. Stratigraphically, the CTPS includes all units within the Wasatch and Green River Formations designated as follows: the main body of the Wasatch Formation, the New Fork, Niland, Red Desert, and Cathedral Bluffs Tongues of the Wasatch Formation, the Luman, Fontenelle, and Tipton Tongues of the Green River Formation, and the Laney and Wilkins Peak Members of the Green River Formation. The base of the petroleum system is placed at the base of the main body of the Wasatch Formation (or the base of equivalent units in the Red Desert Tongue), or at the base of the undifferentiated Wasatch Formation where the formation is not subdivided; the top of the petroleum system is placed at the top of the Green River Formation. Because varying nomenclature has been applied to age equivalent units (members, tongues) in both formations, all named units within either formation may not be represented at any single locality. The petroleum system encompasses about 7,850,000 acres (12,265 square miles) in Wyoming, Colorado, and Utah and includes areas within the Green River, Great Divide, Washakie, and Sand Wash structural basins.

Potential source rocks in the Wasatch–Green River CTPS are primarily lacustrine deposits of organic-rich shale (including oil shale) and mudstone in the Green River Formation, and marginal lacustrine or terrestrial deposits of coal and coaly carbonaceous strata in the Wasatch Formation and, to a lesser degree, the Green River Formation. Lacustrine source rocks contain Type-I and mixed Type-I and Type-III kerogen in strata deposited in lake environments of varying water depths and salinities. Lacustrine units are prevalent in the Luman Tongue and in the Wilkins Peak and Laney Members of the Green River Formation. In the Green River and Washakie Basins, the Luman Tongue generally ranges between 200 and 300 feet in thickness, the Wilkins Peak Member ranges from less than 120 feet to over 1,000 feet, and the Laney Member generally ranges between 1,200 and 1,300 feet.

Coal and coaly carbonaceous units in both formations contain Type-III kerogen. Coal is present in the main body and Red Desert and Niland Tongues of the Wasatch Formation, and in the Luman Tongue of the Green River Formation. Primary Eocene coal depocenters were mainly concentrated in marginal lacustrine environments in the western Washakie Basin and central Great Divide Basin. In the Red Desert Basin area of the central Great Divide Basin as many as 10 coal zones are present within a 1,000-foot-thick coal-bearing interval in the Wasatch Formation. Lenticular coalbeds as thick as 42 feet are present locally, with several beds as thick as 20 feet; most coalbeds, however, average about 7 feet in thickness. In the Vermillion Creek Basin area on the southeast flank of the Rock Springs uplift, coalbeds are distributed within the main body and Niland Tongue of the Wasatch Formation and in the Luman Tongue of the Green River Formation. In this area, the Vermillion Creek coal bed extends throughout an area of 23 square miles and attains a maximum net coal thickness (excluding partings) of 12 feet. The apparent coal rank in the petroleum system varies from subbituminous C to high-volatile C bituminous.

Coalbeds and lacustrine units sampled from outcrops and shallow drill holes in the CTPS have measured thermal maturity (R_o) values generally ranging from 0.20 to 0.61 percent. Green River samples from the Luman Tongue and Wilkins Peak and Laney Members have R_o values ranging from 0.20 to 0.45 percent. R_o values as high as 0.72 percent and averaging about 0.52 percent are reported for coaly samples in the Niland Tongue of the Wasatch Formation (Vermillion Creek coal bed); shale units interbedded with the coal have an average R_o of about 0.42 percent. In most areas of the CTPS, the low thermal maturity of these source rocks will limit the potential for thermogenic oil or gas accumulations. However, because of the widespread occurrence of these organic-rich source rocks, a potential exists for the generation and accumulation of biogenic (microbial) gas.

Two hypothetical, continuous gas assessment units within

the petroleum system have been delineated to address biogenic gas potential: the Wasatch–Green River Coalbed Gas Assessment Unit, and the Wasatch–Green River Continuous Gas Assessment Unit. Formulation of the latter assessment unit stems from current exploration and production tests for gas in the Wilkins Peak Member of the Green River Formation; this potential resource is considered to represent a self-sourced, biogenic shale-gas accumulation. Because exploration for gas in the Wilkins Peak Member is in such an early stage, no quantitative assessment of undiscovered gas resources in the Wasatch-Green River Continuous Gas Assessment Unit was completed. There is currently no commercial production of coalbed gas within the CTPS, and for this reason, coalbed gas wells producing from subbituminous coal in the Fort Union Formation in the Powder River Basin were used as analogs for estimating potential coalbed gas resources in this petroleum system. The mean estimate of undiscovered coalbed gas resources in the Wasatch–Green River Coalbed Gas Assessment Unit is 64.7 billion cubic feet of gas.

Introduction

The Wasatch–Green River Composite Total Petroleum System (CTPS) in the Southwestern Wyoming Province contains source rocks and potential hydrocarbon accumulations within Tertiary (Eocene) strata in the Wasatch and Green River Formations (fig. 1). The petroleum system encompasses about 7,850,000 acres (12,265 mi^2) in Wyoming, Colorado, and Utah (fig. 2) and includes areas within the Green River, Great Divide, Washakie, and Sand Wash structural basins (fig. 3). In the Green River Basin, the CTPS boundary is defined primarily by the outcrop limits of the Wilkins Peak Member of the Green River Formation, exclusive of some Wilkins Peak outcrops proximal to or within the overthrust belt west of the Moxa arch. In the Washakie, Sand Wash, and Great Divide Basins, the petroleum system boundary is defined by the outcrop limits of the Wasatch Formation, or the projection of those limits in areas of Quaternary sedimentary cover. Age equivalent units in the Battle Spring Formation in the northeastern Great Divide Basin are excluded from the CTPS.

Stratigraphically, the CTPS includes all units within the Wasatch and Green River Formations designated as follows: the main body of the Wasatch Formation, the Red Desert, New Fork, Niland, and Cathedral Bluffs Tongues of the Wasatch Formation; the Luman, Fontenelle, and Tipton Tongues of the Green River Formation; and the Laney and Wilkins Peak Members of the Green River Formation (fig. 4). Because varying nomenclature has been applied to age equivalent units (members, tongues) in both formations, all named units within either formation may not be represented at any single locality. For the purposes of this report, the name Tipton Tongue, which is equivalent to the Tipton Shale Member of the Green River Formation as described by Bradley (1964), will be used. Additionally, in the central part of the Great Divide Basin, Pipiringos (1961) applied the name Red Desert Tongue of the Wasatch Formation to a succession of sandstone, shale, oil shale, and coal beds underlying the Luman Tongue of the Green River Formation. The Red Desert Tongue is equivalent (in part) to the main body of the Wasatch Formation and thus is included within the Wasatch–Green River CTPS. The base of the petroleum system is placed at the base of the main body of the Wasatch Formation (or the base of equivalent units in the Red Desert Tongue), or at the base of the undifferentiated Wasatch Formation in areas where the formation is not subdivided. The top of the CTPS is defined by the top of the Green River Formation, which is overlain by and intertongues with the Bridger Formation or age equivalent units in the Washakie Formation.

In general, the juxtaposition of laterally equivalent units in the Wasatch and Green River Formations reflects the intertonguing of alluvial and lacustrine facies. Alluvial facies (for example, fluvial sandstone, flood-plain shale, and coal) are more predominant in the Wasatch Formation and lacustrine facies (for example, oil shale, evaporites, and carbonates) are more characteristic of the Green River Formation. Estimates of the combined thickness of the Wasatch and Green River Formations in selected wells in the Green River Basin range from about 3,000 to 6,200 ft; in the deep Washakie Basin, the combined thickness is estimated to be about 8,050 ft (L.N.R. Roberts, U.S. Geological Survey, oral commun., 2003). Because of facies variations and intertonguing relations, the thickness of individual units within both formations varies markedly throughout the province. In a measured reference section of Eocene rocks extending from the southeastern part of the Green River Basin to the west flank of the Rock Springs uplift, Roehler (1992a) reports a thickness of 1,236 ft for the main body of the Wasatch Formation, 482 ft for the Niland Tongue of the Wasatch Formation, 229 ft for the Luman Tongue of the Green River Formation, 167 ft for the Tipton Tongue of the Green River Formation, 1,068 ft for the Wilkins Peak Member of the Green River Formation, and 1,299 ft for the Laney Member of the Green River Formation. The total thickness for Wasatch–Green River CTPS units in this measured section in the Green River Basin is 4,481 ft. In the southwestern part of the Washakie Basin, southeast of the Rock Springs uplift, Roehler (1992a) reports a thickness of 1,691 ft for the main body of the Wasatch Formation, 329 ft for the Niland Tongue of the Wasatch Formation, 827 ft for the Cathedral Bluffs Tongue of the Wasatch Formation, 293 ft for the Luman Tongue of the Green River Formation, 183 ft for the Tipton Tongue of the Green River Formation, 119 ft for the Wilkins Peak Member of the Green River Formation, and 1,320 ft for the Laney Member of the Green River Formation. The total thickness of CTPS units in this measured section in the Washakie Basin is 4,762 ft. In the central part of the Great Divide Basin, Pipiringos (1961) reports that the Red Desert Tongue of the Wasatch Formation ranges from 1,000 to 1,500 ft in thickness, the Niland Tongue of the Wasatch Formation ranges from 180 to 400 ft thick, and the Cathedral Bluffs Tongue of the Wasatch Formation ranges from 1,400 to

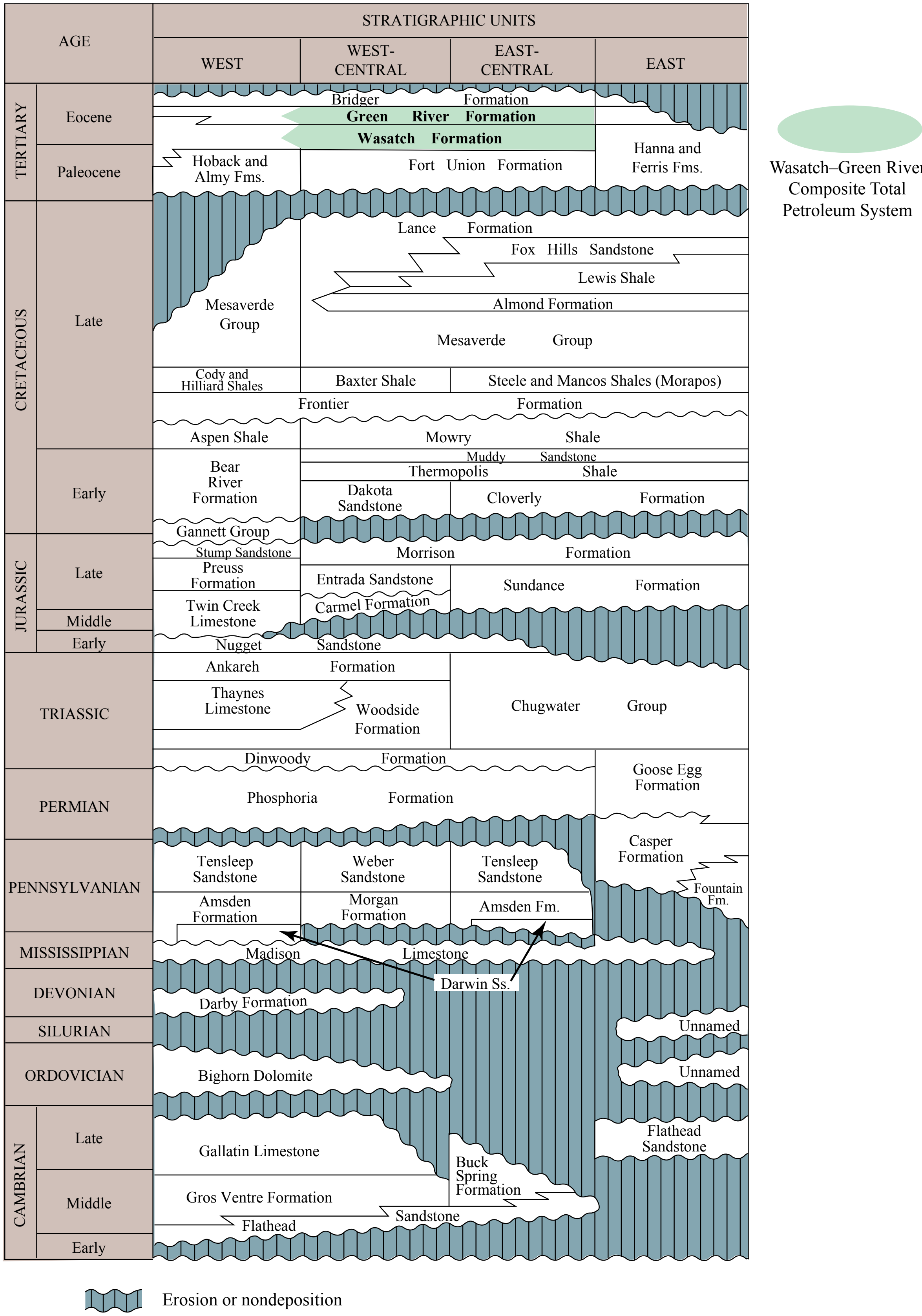


Figure 1. Generalized stratigraphic chart for the Southwestern Wyoming Province in Wyoming, Colorado, and Utah showing units in the Wasatch–Green River Composite Total Petroleum System. Modified from Law (1996). Ss., Sandstone; Fm., Formation.

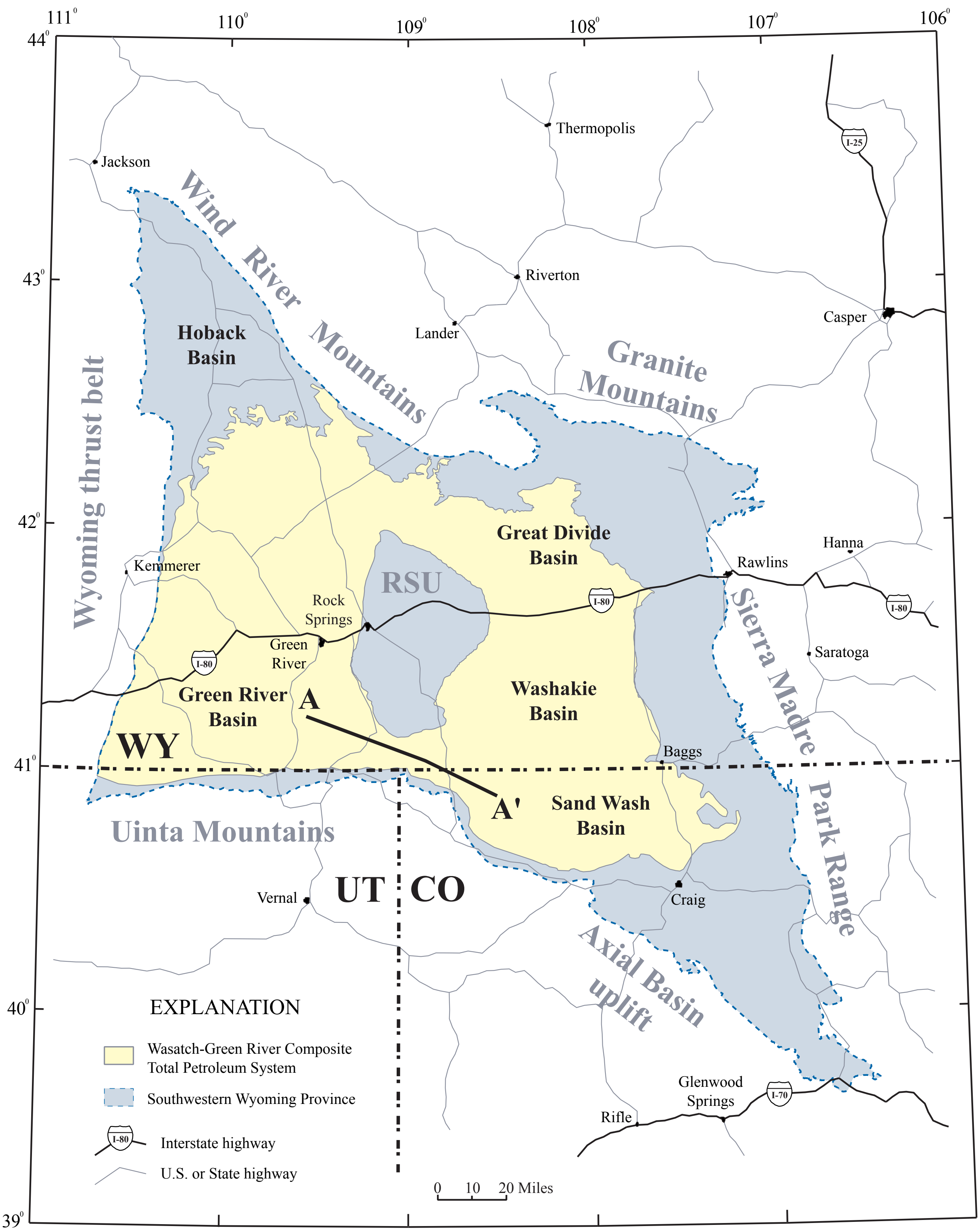


Figure 2. Location of the Wasatch–Green River Composite Total Petroleum System in the Southwestern Wyoming Province, Wyoming, and Colorado, and Utah. Cross section AA′ is shown in figure 4. RSU, Rock Springs uplift. Boundaries of the petroleum system are based on distribution of Eocene geologic units in Green (1992) and Green and Drouillard (1994).

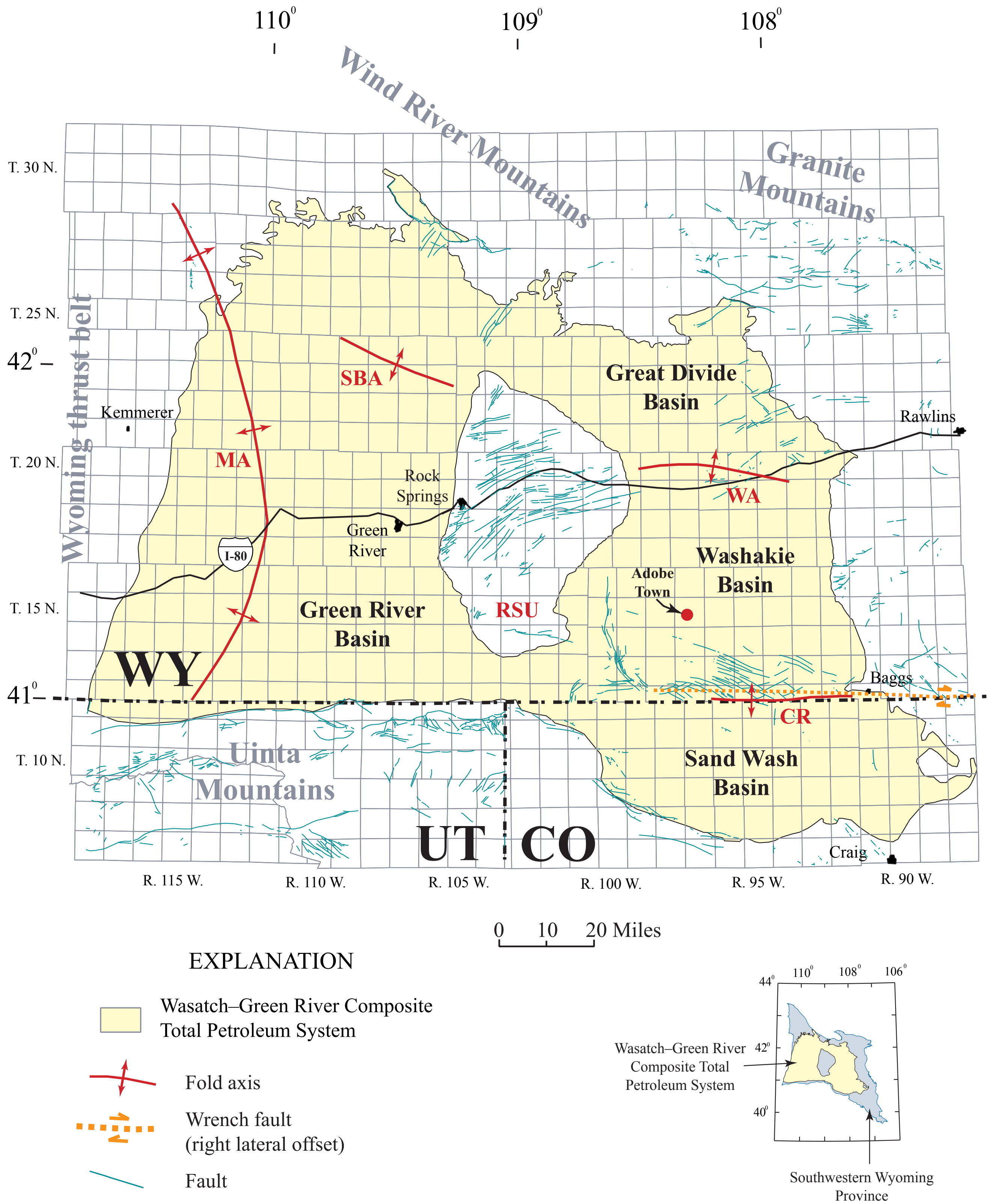


Figure 3. Major structural elements in the Wasatch–Green River Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. CR, Cherokee ridge; WA, Wamsutter arch; SBA, Sandy Bend arch; MA, Moxa arch; RSU, Rock Springs uplift. Burial-history interpretations for the Adobe Town well are reported in Roberts and others (Chapter 3, this CD–ROM).

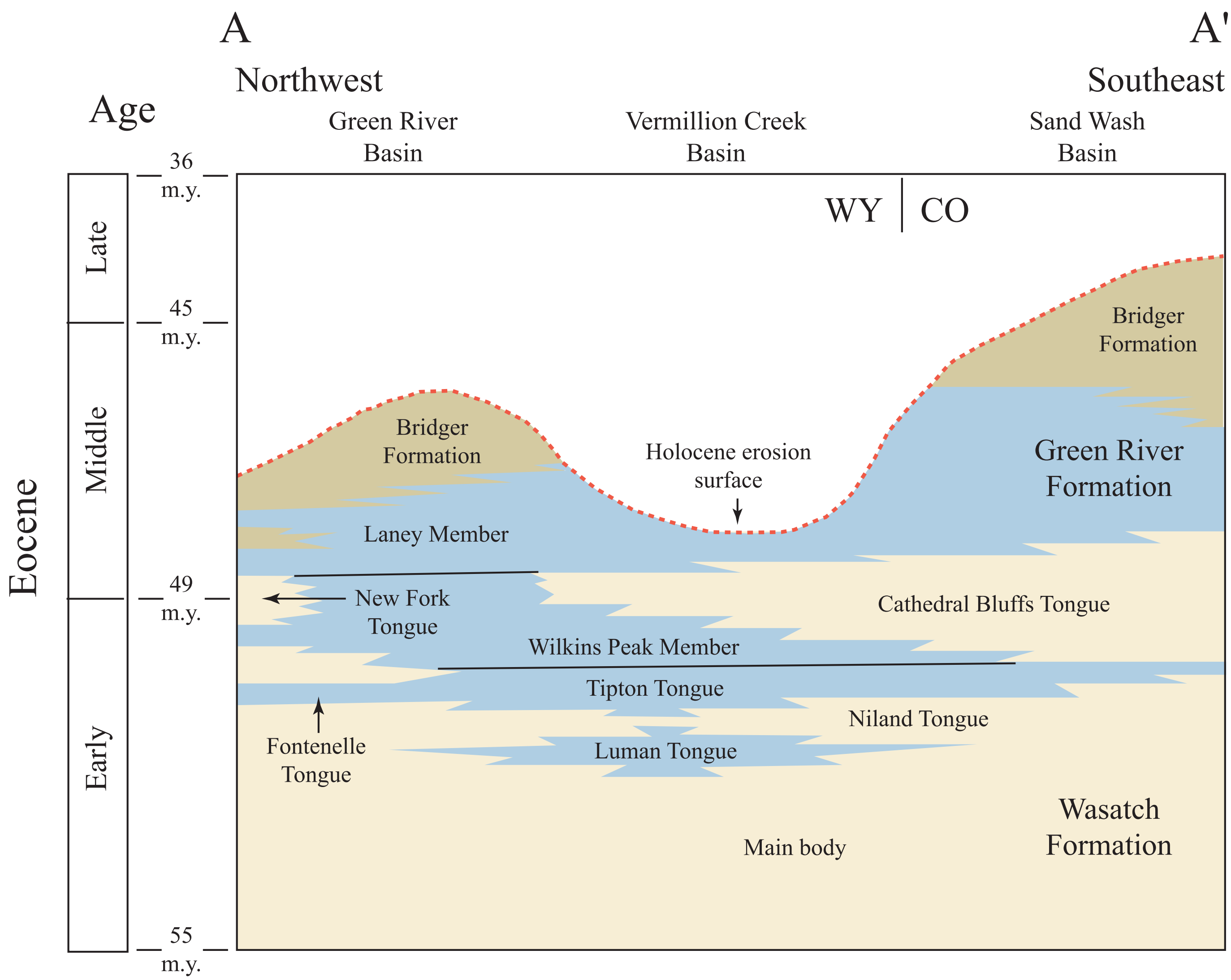


Figure 4. Cross section showing stratigraphic units within the Wasatch and Green River Formations in southwestern Wyoming (Green River Basin) and northwestern Colorado (Sand Wash Basin). Formations are identified by color. Cross section location is shown in figure 2. Modified from Roehler (1987). m.y., million years.

1,600 ft thick. In this same area, the Luman Tongue of the Green River Formation ranges from 180 to 270 ft thick, the Tipton Tongue of the Green River Formation ranges from 280 to 310 ft thick, and the Laney Member of the Green River Formation is about 200 ft thick. Based on the minimum and maximum thickness reported for individual units, the combined Wasatch and Green River Formations ranges from about 3,200 to 4,300 ft thick in the central Great Divide Basin.

Significant oil and associated gas resources have been generated from lacustrine source rocks within the Green River Formation in the Uinta Basin of Utah (for example, see Ruble and others, 2001; Dubiel, 2003), and studies of lacustrine lithologies in the Green River Formation in southwestern Wyoming indicate that similar organic-rich source rocks are present in the Wasatch–Green River CTPS (for example, see Horsfield and others, 1994; Carroll and Bohacs, 2001). In contrast to the Uinta Basin, however, lacustrine and marginal lacustrine rocks in the Wasatch and Green River Formations in much of southwestern Wyoming are thermally immature ($R_o < 0.60$ percent; for example, see Horsfield and others, 1994; Carroll and Bohacs, 2001; Roberts and others, Chapter 3, this volume); thus, the potential for generation of significant oil or thermogenic gas is considered low. However, because of the widespread occurrence of organic-rich source rocks (including oil shale and coal), a potential exists for the generation and accumulation of biogenic (microbial) gas, and the Wasatch–Green River CTPS is defined primarily to address this gas potential.

Two continuous gas assessment units within the petroleum system have been delineated: the Wasatch–Green River Coalbed Gas Assessment Unit, and the Wasatch–Green River Continuous Gas Assessment Unit. Formulation of the latter assessment unit stems from current exploration and production tests of gas in the Wilkins Peak Member of the Green

River Formation (IHS Energy Group, 2001; Wyoming Oil and Gas Conservation Commission, 2002). In this assessment, this potential gas resource is considered to represent a self-sourced, biogenic shale-gas accumulation, and although there is some question as to whether Wilkins Peak gas is biogenic or an early phase of thermogenic gas (Coleman, 2001), the definition and general characteristics of the assessment unit (source, reservoirs, and so forth) are applicable to either case. Currently, there is no commercial production of either coal-bed gas or lacustrine shale gas within the CTPS, and for this reason, these assessment units are considered hypothetical. In addition, because exploration for gas in the Wilkins Peak Member is in such an early stage, and published data on the characteristics of the gas accumulation are sparse, no quantitative assessment of undiscovered gas resources in the Wasatch–Green River Continuous Gas Assessment Unit was completed.

Acknowledgments

I would like to thank Mark Kirschbaum for his assistance in defining the boundaries of the Wasatch–Green River petroleum system and Laura Roberts (USGS) for her efforts in generating key maps depicting these boundaries. In addition, Paul Lillis (USGS), Steve Condon (USGS), Tom Judkins (USGS), and Katherine Varnes (USGS) provided thoughtful and comprehensive reviews that greatly improved this manuscript.

Source Rocks

Potential source rocks in the Wasatch–Green River CTPS are primarily lacustrine deposits of organic-rich shale (including oil shale) and mudstone in the Green River Formation and marginal lacustrine or terrestrial deposits of coal and coaly carbonaceous strata in the Wasatch Formation and to a lesser degree, the Green River Formation. Lacustrine source rocks contain Type-I and mixed Types-I and III kerogen in strata deposited in lake environments of varying water depths and salinities (Grabowski and Bohacs, 1996; Carroll and Bohacs, 2001); coal and coaly carbonaceous units in both formations contain Type-III kerogen. Carroll and Bohacs (2001) grouped potential source rocks in the Green River Formation in terms of three primary organic facies: an algal-terrestrial organic facies, an algal-organic facies, and a hypersaline algal-organic facies.

The algal-terrestrial organic facies is representative of potential source rocks in the Luman Tongue of the Green River Formation and the Niland Tongue of the Wasatch Formation (fig. 4) (Carroll and Bohacs, 2001). The Luman Tongue, which ranges from about 180 to 390 ft in thickness (for example, see Pipiringos, 1961; Bradley, 1964; Roehler, 1992a) consists of low-grade oil shale, calcareous sandstone, siltstone, mudstone, and thin coalbeds (Bradley, 1964). It is estimated that oil yields from oil shale within the Luman Tongue are typically less than 15 gallons/ton (for example, see Roehler, 1992b). The Niland Tongue ranges from about 180 to 400 ft in thickness (Pipiringos, 1961) and consists primarily of lenticular sandstone beds, mudstone, carbonaceous shale and coal (Bradley, 1964). Potential source rocks in the algal-terrestrial organic facies contain a mix of aquatic organic matter (algal material; Type-I kerogen) and terrestrial organic matter (land plant-derived material; Type-III kerogen) (for example, see Carroll and Bohacs, 2001). The total organic carbon (TOC) in Luman Tongue samples ranges from 1 to 59.2 percent, and Rock-Eval hydrogen indices (HI) range from 55 to 985 (Carroll and Bohacs, 2001, after Horsfield and others, 1994). Total organic carbon values in organic mudstone units in both the Luman and Niland Tongues typically range from 2 to 8 percent; higher TOC values (greater than 50 percent) reflect samples from coaly lithologies (Carroll and Bohacs, 2001). In studies of the Luman Tongue in the Washakie Basin, Horsfield and others (1994) noted that the highest concentrations of organic matter (mixed aquatic and terrestrial sources) were found in lake margin sediments, whereas only low concentrations of organic matter from aquatic sources were present in profundal (deeper) lake sediments.

Potential source rocks in the Wilkins Peak Member of the Green River Formation (fig. 4) are present in the hypersaline algal organic facies (Carroll and Bohacs, 2001). The Wilkins Peak Member is noted for an abundance of saline minerals and bedded trona deposits within a succession characterized primarily by sandstone, siltstone, mudstone, clay-shale, and oil shale; beds of marlstone, algal limestone, and clay pebble conglomerate are present locally (Bradley, 1964; Roehler, 1992a). At the type locality on Wilkins Peak in the Green River Basin, the member is about 900 ft thick (Bradley, 1964), and in measured reference sections in the southeastern Green River Basin and in the southwestern Washakie Basin, the member is reported to be 1,068 ft thick and 119 ft thick, respectively (Roehler, 1992a). In general, Wilkins Peak strata represent alternating stages of saline lacustrine deposition and periods of lake retreat and drying (Roehler, 1992b). Oil shale is present in the Wilkins Peak in both the Washakie Basin and in the Green River Basin, where Roehler (1992b) identified as many as 77 beds of oil shale. Oil shale units are typically thin, ranging from inches to several feet in thickness (see, for comparison, Bradley, 1973; Sullivan, 1985). Estimated oil yields in the Washakie Basin are generally less than 15 gallons/ton but are locally as high as 22.7 gallons/ton (Trudell and others, 1973; Roehler, 1992b). Total organic carbon values for Wilkins Peak organic-rich lithologies range from 4.1 to 20.0 percent, and HI varies from 32 to 1001 (Grabowski and Bohacs, 1996; Carroll and Bohacs, 2001). Type-I kerogen is predominant in organic-rich, dolomitic lime mudstone units that range from 1 to 5 ft thick (Grabowski and Bohacs, 1996); some lithologies can include mixed Types-I and III kerogen (Carroll and Bohacs, 2001). Total organic carbon values are generally lowest in littoral (shallow) and marginal lacustrine (lake-plain) mudstone and highest in sublittoral (profundal) mudstone and shale, suggesting that highest organic enrichment took place when the lakes were deepest (Carroll and Bohacs, 2001).

Organic-rich, laminated mudstone in the Laney Member of the Green River Formation (fig. 4) contains algal-derived organic matter characteristic of the algal organic facies (Carroll and Bohacs, 2001). The Laney Member is generally characterized by interbedded marlstone, sandstone, siltstone, shale, and oil shale (Bradley, 1964). In the Washakie Basin, the Laney Member ranges from less than 400 to about 1,900 ft in thickness, and in the Green River Basin, near the town of Green River, Wyoming (fig. 2), the member is more than 600 ft thick (Bradley, 1964). Estimated oil yields from oil shale in the Laney Member range from about 15 gallons/ton to more than 40 gallons/ton locally in the Washakie Basin (Roehler, 1992b). Overall TOC values for Laney Member samples generally range from about 1.5 to 30 percent, and HI ranges from about 52 to 1,003 (Carroll and Bohacs, 2001, after Horsfield and others, 1994; Grabowski and Bohacs, 1996). Profundal lime mudstones enriched in Type-I kerogen in the Laney Member have up to 30 percent TOC, whereas littoral shales have mixed Types-I and III kerogen and TOC values of about 7 percent (Grabowski and Bohacs, 1996). Total organic carbon values in the LaClede Bed in the lower part of the Laney Member (Roehler, 1992a) are reported to be as high as 20 percent (Carroll and Bohacs, 2001).

Coal composed primarily of Type-III kerogen is present in the main body and the Red Desert and Niland Tongues of the Wasatch Formation, and to a lesser degree, in the Luman Tongue of the Green River Formation. Although minor, sporadic coalbeds may be present in the Wasatch Formation in much of the CTPS, primary Eocene coal depocenters were mainly concentrated in marginal lacustrine environments in the western Washakie Basin and central Great Divide Basin; many of the coalbeds in these areas are uranium-bearing (for example, see Pipiringos, 1961; Masursky, 1962; Glass, 1981; Roehler, 1987). In the Red Desert Basin area of the central Great Divide Basin (fig. 5), Masursky (1962) identified seven major coal zones within a 700-ft-thick coal-bearing interval in the main body of the Wasatch Formation (fig. 6). Within this interval, lenticular coalbeds as thick as 42 ft are present locally, with several beds as thick as 20 ft; most coalbeds, however, average about 7 ft in thickness. In an adjacent study area to the west, Pipiringos (1961) identified 10 coal zones within an interval of about 1,000 ft (fig. 6). In this area, coal is present in the Red Desert and Niland Tongues of the Wasatch Formation, and in the Luman Tongue of the Green River Formation. About 30 coalbeds were observed in outcrops, with coalbeds ranging in thickness from a few inches to as much as 21 ft (Pipiringos, 1961). In the Vermillion Creek Basin area on the southeast flank of the Rock Springs uplift (fig. 5), coalbeds are also distributed within the main body and Niland Tongue of the Wasatch Formation and in the Luman Tongue of the Green River Formation (fig. 7). In measured sections of the Niland Tongue in the Vermillion Creek Basin area, Roehler (1987) reports coal thickness typically ranging from a few inches to several feet. An exception to the generally thin and lenticular nature of coalbeds in the Niland Tongue in this area is the Vermillion Creek coalbed, which is present throughout an area of 23 mi^2 and attains a maximum net coal thickness (excluding partings) of 12 ft locally (Ellis, 1987).

Analyses (as-received) of samples from thicker Eocene coalbeds in the Great Divide Basin indicate an average moisture content of about 21 percent, an average ash yield of about 16 percent, an average total sulfur content of 2.5 percent, and an average heat-of-combustion value of about 7,900 Btu/lb (Glass, 1981, after Smith and others, 1972). Apparent coal rank varies from subbituminous C to B (Pipiringos, 1961; Masursky, 1962). Higher rank Eocene coal is present in the Niland Tongue of the Wasatch Formation in the Vermillion Creek Basin area, where the Vermillion Creek coalbed has an apparent rank of high-volatile C bituminous (Hatch, 1987). As-received moisture values for the Vermillion Creek coal typically range from about 11 to 15 percent, and average as-received values for ash yield and total sulfur content are 18.2 and 5.6 percent, respectively; heat-of-combustion values (moist, mineral-matter-free basis) average 11,556 Btu/lb (Ellis, 1987; Hatch; 1987).

In general, lacustrine source rocks composed of Type-I or mixed Types-I and III kerogen are considered to be predominantly oil prone, and terrestrial source rocks such as coal, composed primarily of Type-III kerogen are considered to be gas prone. The oil-prone nature of Green River lacustrine source rocks containing Type-I or mixed Types-I and III kerogen in the Green River Basin is supported by studies of Horsfield and others (1994), Carroll and Bohacs (2001), as well as in studies of the Green River Formation in the Uinta Basin (Ruble and others, 2001). The gas-prone nature of source rocks composed mainly of Type-III organic matter is discussed in studies of gas resources in other Rocky Mountain basins by Meissner (1984), Law and others, (1989), and Law (1996). In addition, all source-rock types described previously are interpreted to have the potential to generate biogenic gas.

Source Rock Maturation and Hydrocarbon Migration

Potential source rocks in the Wasatch and Green River Formations sampled from outcrops and shallow (less than 1,000 ft) drill holes in the CTPS have measured thermal maturity (R_o) values ranging from 0.20 to 0.61 percent (Bostick and others, 1987; Carroll and Bohacs, 2001). Green River samples from predominantly lacustrine strata in the Luman Tongue and Wilkins Peak and Laney Members have R_o values ranging from 0.20 to 0.45 percent (Carroll and Bohacs, 2001). R_o values as high as 0.72 percent and averaging about 0.52 percent are reported for coaly samples in the Niland Tongue of the Wasatch Formation (Vermillion Creek coal bed); shale units interbedded with the coal have an average R_o of about 0.42 percent (Bostick and others, 1987).

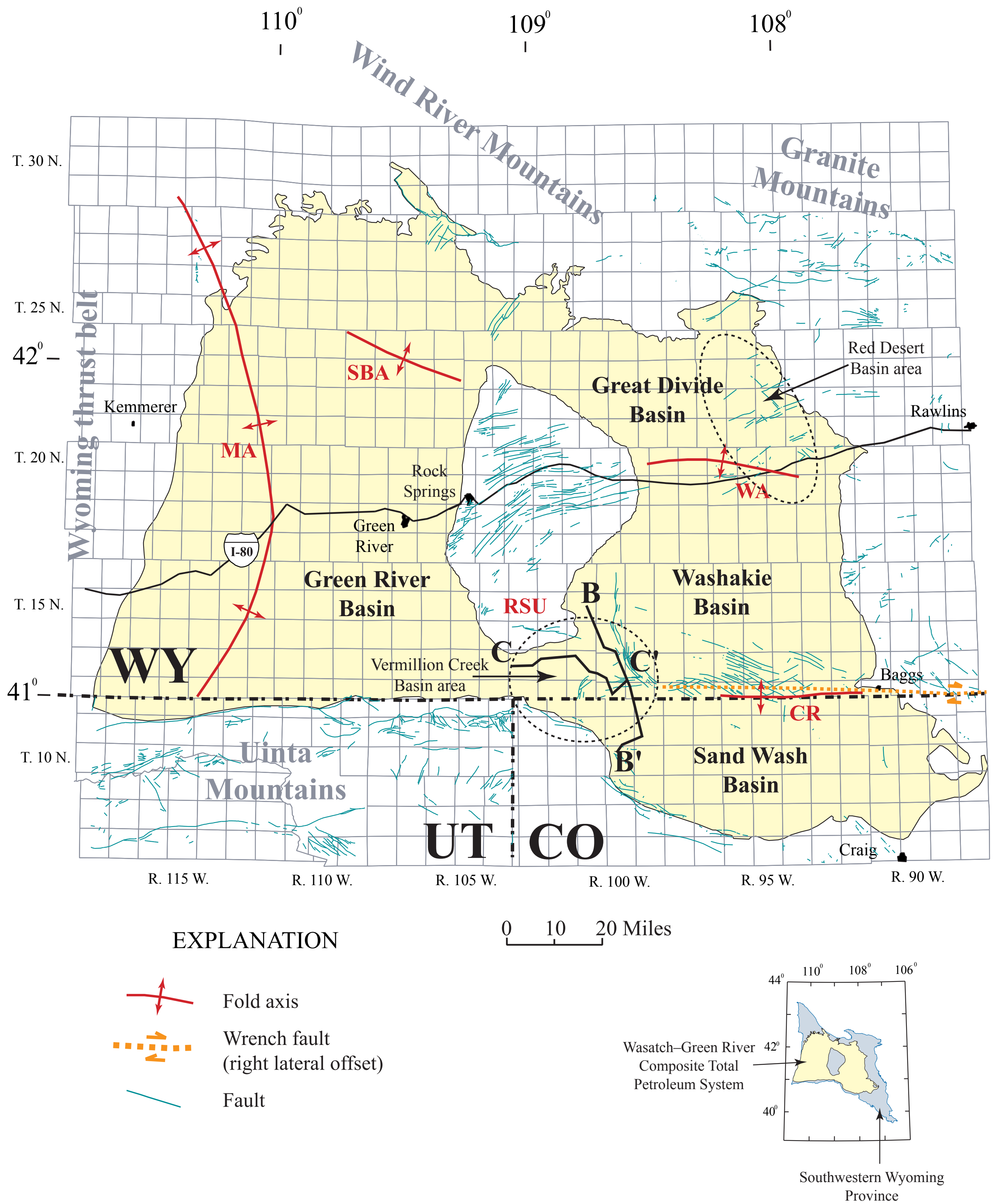


Figure 5. Location of major Eocene coal deposits (Vermillion Creek Basin and Red Desert Basin) in the Wasatch–Green River Composite Total Petroleum System in the Southwestern Wyoming Province, Wyoming, and Colorado, and Utah. Cross sections B–B′ and C–C′ are shown in figure 7. Location and extent of Red Desert Basin area is based on Pipiringos (1961) and Masursky (1962). Vermillion Creek Basin area is based on Roehler (1987). CR, Cherokee ridge; WA, Wamsutter arch; SBA, Sandy Bend arch; MA, Moxa arch; RSU, Rock Springs uplift.

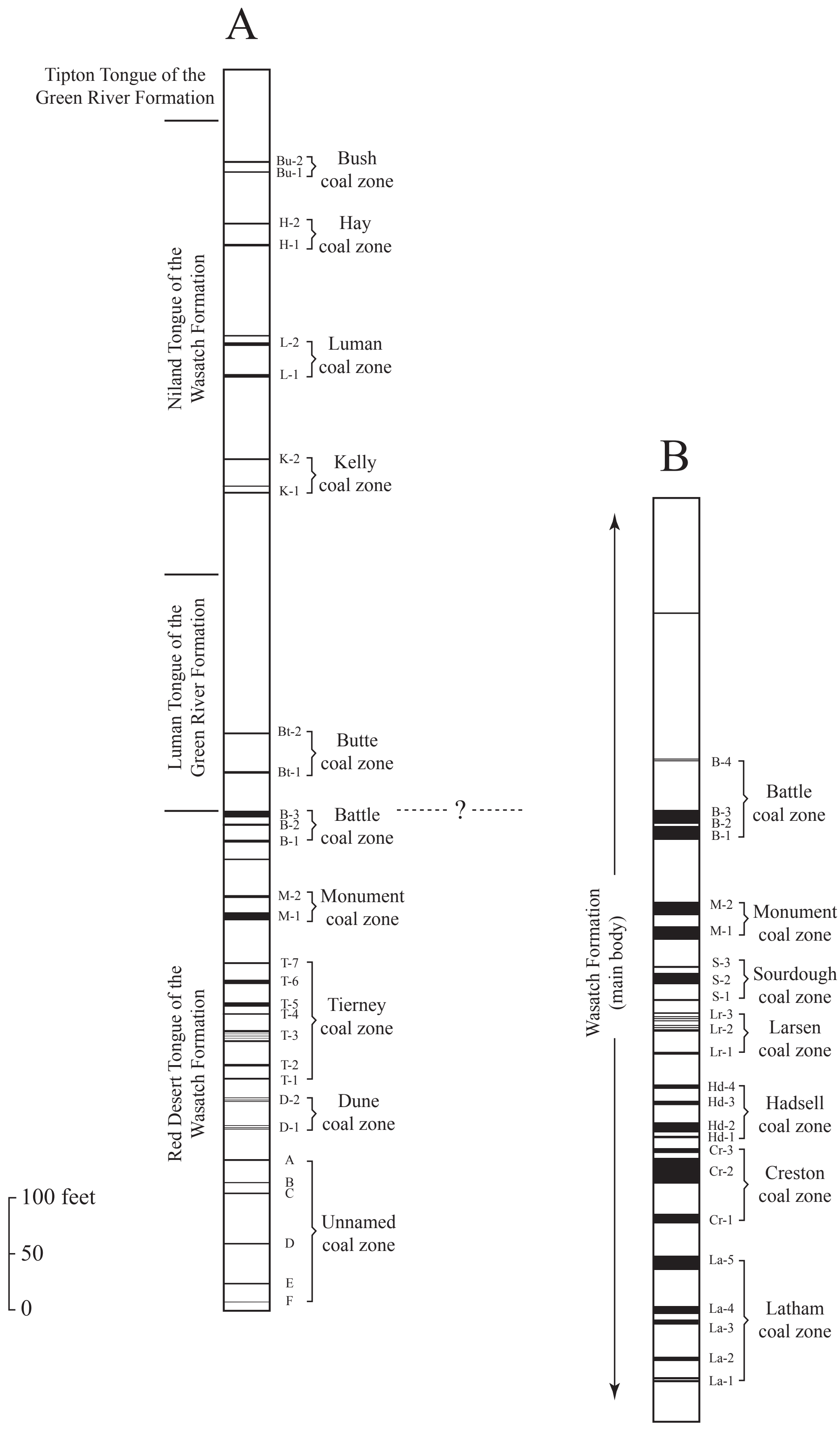


Figure 6. Stratigraphic columns showing the distribution and nomenclature for Eocene-age coal zones in the Wasatch and Green River Formations in the Red Desert Basin area of the Great Divide Basin, Wyoming. Column A based on Pipiringos (1961); column B based on Masursky (1962). Coal thickness not to scale.

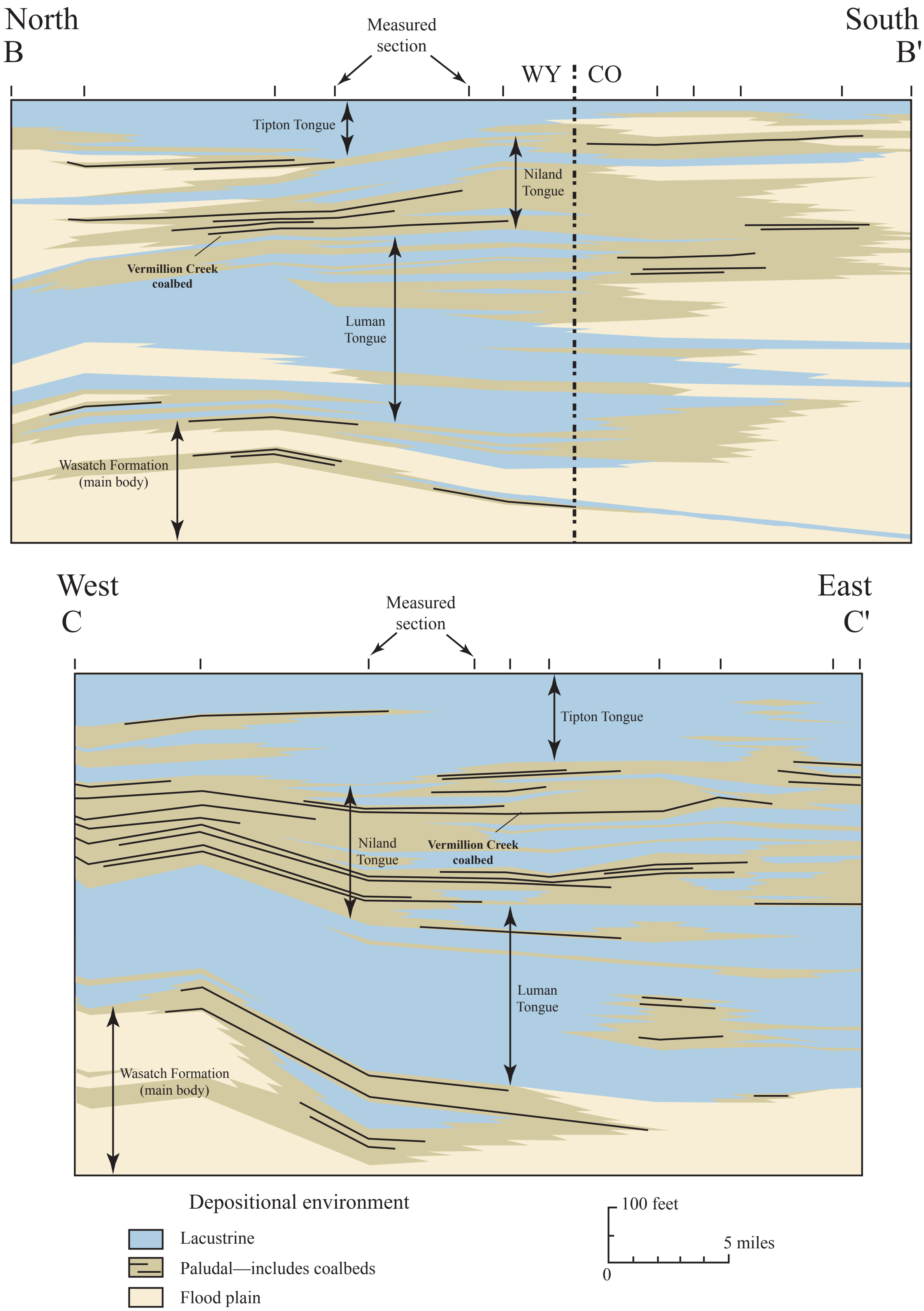


Figure 7. Cross sections B–B′ and C–C′ showing the stratigraphy and distribution of Eocene-age coalbeds in the Vermillion Creek Basin area of southwestern Wyoming. Cross-section locations are shown in figure 5. The Luman and Tipton Tongues are members of the Green River Formation; the Niland Tongue is a member of the Wasatch Formation. Modified from Roehler (1987).

Tegelaar and Noble (1994) and Ruble and others (2001) suggest that early oil generation in Green River (Type-I) source rocks occurs at thermal maturity levels ranging between 0.8 and 1.0 percent. Potential lacustrine source rocks in the Luman Tongue, Laney Member, and Wilkins Peak Member have reported R_o values of less than 0.50 percent, which is significantly below the interpreted level for oil generation. Potential source rocks (especially coal) composed predominantly of gas-prone, Type-III organic matter have the potential to generate gas at thermal maturity (R_o) levels of about 0.50 to 0.60 percent (see, for comparison, Levine, 1993; Rice, 1993; Roberts and others, Chapter 3, this volume), and this level of maturity has been documented in coal samples from the Vermillion Creek Basin (fig. 5) (Bostick and others, 1987). However, significant thermogenic gas generation in Type-III organic matter is thought to occur at higher R_o levels of about 0.73 to 0.80 percent (for example, see Law, 1984; Meissner, 1984; Johnson, 1989). In most areas of the CTPS, this level of maturity has not been reached, except possibly in the deep, central portion of the Washakie Basin, where interpretations of burial history for the Adobe Town well (fig. 3) (Roberts and others, Chapter 3, this volume) indicate that oil-prone and gas-prone source rock intervals in both formations are at thermal maturity (R_o) levels ranging between 0.5 and 0.9 percent. This area of higher thermal maturity may have a greater potential for hydrocarbon generation, particularly in more deeply buried, stratigraphically lower units in the CTPS. In most areas, however, the generally low thermal maturity of both oil-prone lacustrine (Type-I) and gas-prone terrestrial (Type-III) source rocks would seem to limit the potential for any significant oil or thermogenic gas accumulations in either conventional or continuous-type accumulations in most of the CTPS.

Currently (2004), no published evidence exists of long-distance hydrocarbon migration and accumulation in discrete, conventional reservoirs sourced by the CTPS units described above. Because the greatest potential for hydrocarbon resources in this CTPS is interpreted to relate primarily to biogenic gas generation in coal bed and shale gas accumulations, assessment units are anticipated to be of the continuous (unconventional) type. As such, these accumulations are characterized by a pervasive gas charge in close association with source-rock intervals, and migration distances are negligible (for example, see Schmoker, 1996; Curtis, 2002). However, limited migration of a free gas component could result in gas accumulation in closely associated fracture sets or in more porous sedimentary units (for example, fluvial and marginal lacustrine sandstone) stratigraphically juxtaposed with source rocks.

Reservoir Rocks, Traps, and Seals

A common characteristic of biogenic gas accumulations is that source rocks also serve as primary reservoirs. Coal beds in the Wasatch Formation (main body and Red Desert and Niland Tongues) are obvious reservoirs for potential coalbed-gas accumulations, with more limited coalbed-gas reservoirs in lenticular coal of the Luman Tongue in the Green River Formation. Coalbed gas may occur as sorbed gas on coal bed surfaces, free gas in pores and fractures (cleats), and as dissolved gas in ground water within the coal beds (Rightmire, 1984). Retention of coalbed-gas resources may depend to some degree on “hydrologic” traps, whereby contained water and associated hydrostatic pressure within the coal prohibit 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.

Organic-rich, lacustrine shale (including oil shale) in Green River units such as the Wilkins Peak Member could also be considered as a primary reservoir for biogenic, shale-gas accumulation. Similar to coalbed gas, shale-gas accumulations can include sorbed gas (on kerogen and clay-particle surfaces), free gas in natural fractures and intergranular pores, and gas dissolved in kerogen, bitumen, and water, if present (for example, see Curtis, 2002). Because of the limited exploration of Wilkins Peak gas, data specific to reservoir lithology and physical characteristics of the accumulation are lacking. It is presumed that shale reservoirs are of low permeability and that natural fractures or well stimulation is critical for the producibility of gas. Evaporites (for example, trona), which are interbedded with some oil-shale beds in certain areas of the CTPS (for example, see Culbertson, 1971), as well as impermeable, clay-rich units that are common in Green River rocks might form effective seals. Fracture systems, however, could limit the effectiveness of stratigraphic seals if fractures pervade most of the stratigraphic section. Typically, traps in shale-gas systems are subtle, and gas-charged strata are anticipated to cover a large geographic area (for example, see Curtis, 2002).

Assessment Units—Wasatch–Green River Composite Total Petroleum System

The Wasatch–Green River Composite Total Petroleum System includes one hypothetical continuous gas assessment unit (50370961) and one hypothetical coalbed-gas assessment unit (50370981). A chart summarizing major geologic events (timing of deposition, gas generation, and so forth) within these assessment units is shown in figure 8.

50370961: Wasatch–Green River Continuous Gas Assessment Unit

The Wasatch–Green River Continuous Gas Assessment Unit (fig. 9) covers an area of about 3,350,000 acres (5,234 mi^2). The assessment unit boundary reflects the estimated

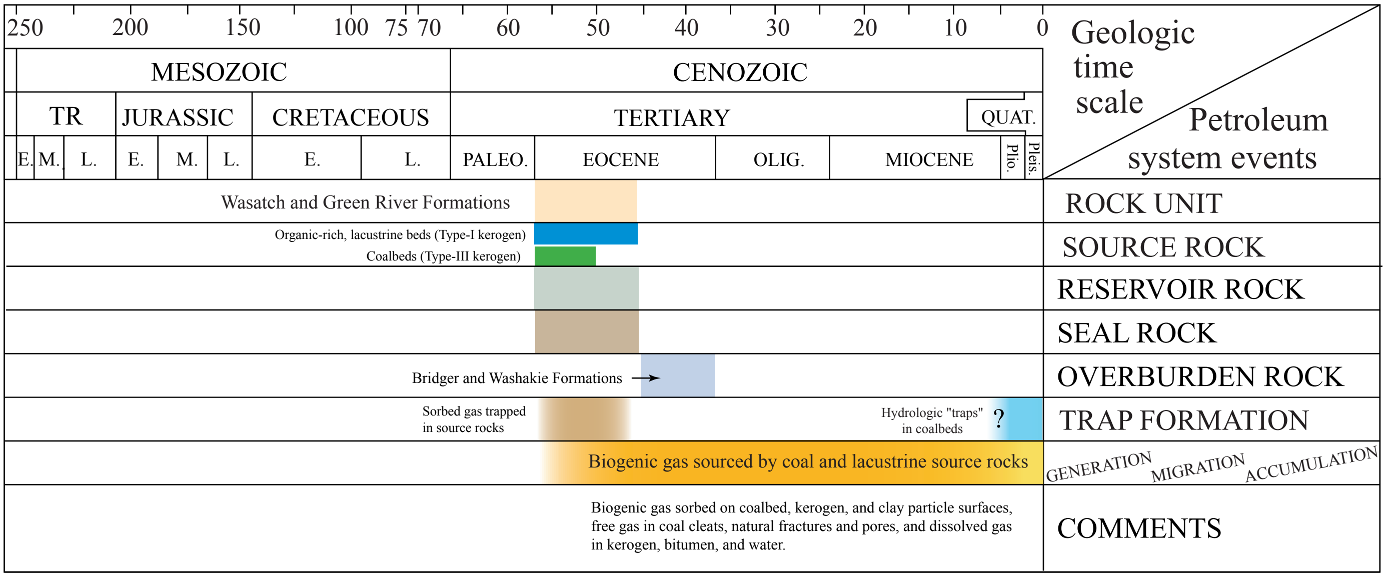


Figure 8. Events chart showing the interpreted timing of elements and processes related to potential gas generation and accumulation in the Wasatch–Green River Continuous Gas Assessment Unit (50370961) and Coalbed Gas Assessment Unit (50370981), Wasatch–Green River Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. Tr, Triassic; Plio., Pliocene; Pleis., Pleistocene; E., Early; M., Middle; L., Late. Events chart format modified from Magoon and Dow (1994).

extent of the Wilkins Peak stage of Gosiute Lake (Bradley, 1964), and the boundary is defined by the outcrop limits of the Wilkins Peak Member, exclusive of some outcrops proximal to or within the overthrust belt west of the Moxa arch. Although other lacustrine intervals in the Green River Formation in this area (Luman Tongue and Laney Member) might also have a similar potential for biogenic gas generation, the assessment unit as defined here is restricted to the Wilkins Peak Member, primarily because current exploration and available production test data (Wyoming Oil and Gas Conservation Commission, 2002) relate solely to this interval.

The assessment unit is hypothetical and is interpreted to be a biogenic, shale-gas accumulation sourced by organic-rich lacustrine strata (including oil shale) composed primarily of Type-I kerogen (Grabowski and Bohacs, 1996; Carroll and Bohacs, 2001). As described previously, however, Coleman (2001) suggests that Wilkins Peak gas could represent an early phase of thermogenic gas. In either case, the assessment unit can be characterized as a continuous accumulation, with potential gas charge in close proximity to source rock units. Organic-rich strata (such as oil shale) likely serve as primary source and reservoir rocks. Data from 28 wells drilled southwest of the town of Green River, Wyoming (fig. 9), primarily in T. 17 N., R. 107-108 W., indicate that tested intervals in the Wilkins Peak range in depth from 1,000 to 2,000 ft (Wyoming Oil and Gas Conservation Commission, 2002). The duration of the reported testing varied from 1 to 12 months, and most wells (23 of the 28) reported production over a period of 6 months or more, between the summer of 2001 and the spring of 2002. Cumulative production ranged from 4 to 1,719 thousand cubic feet (MCF) of gas. The maximum reported production during one month from one well was 875 MCF; however, the maximum, single month production in 17 of the 28 wells was less than 100 MCF (Wyoming Oil and Gas Conservation Commission, 2002). In all wells, there was no reported production of water.

No quantitative estimate of undiscovered gas resources was completed for this assessment unit, primarily because current testing of the Wilkins Peak is restricted to a very small area of the province (fig. 9), and publicly available data on the physical aspects of the accumulation, such as gas content data, reservoir characteristics, and so forth, are lacking. In addition, many of the potential analog shale-gas accumulations within the United States (for example, see Curtis, 2002) differ with respect to source rock (kerogen) type and thermal maturity, and are limited in usefulness. To some degree, gas accumulation in the Wilkins Peak Member might compare to shallow (less than 2,000 ft) shale gas produced from the Antrim Shale in the Michigan Basin. Although the Antrim Shale was deposited in a marine environment as opposed to the lacustrine depositional setting of the Wilkins Peak Member, aspects of the Antrim Shale, such as its low thermal maturity (0.4–0.6 percent R_o) and kerogen type (Type I) (for example, see Martini and others, 1996; Schoell and others, 1997) are comparable to the Wilkins Peak Member. Gas in the Antrim Shale is reported to include thermogenic and biogenic components. Biogenic gas is the primary constituent, although an increased thermogenic component (up to 20–25 percent) is present in deeper areas of the basin (Martini and others, 1996; Curtis, 2002). Wells located in the major producing trend of the Antrim Shale yield, on average, about 116 MCF of gas per day and 30 barrels of water (Curtis, 2002). Percolation of fresh,

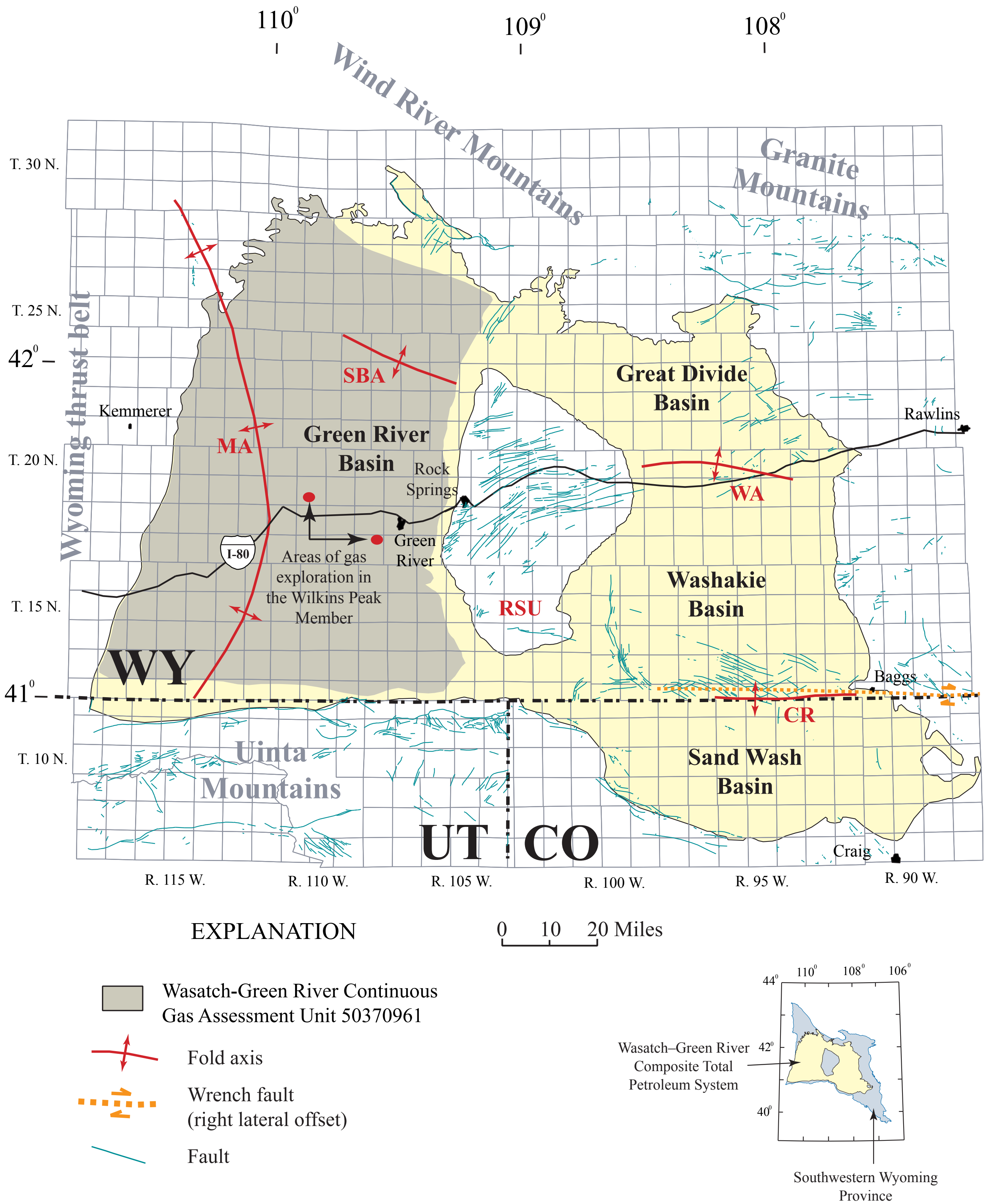


Figure 9. Boundary and extent of the Wasatch–Green River Continuous Gas Assessment Unit (50370961) in the Wasatch–Green River Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. CR, Cherokee ridge; WA, Wamsutter arch; SBA, Sandy Bend arch; MA, Moxa arch; RSU, Rock Springs uplift. Areas of gas exploration in the Wilkins Peak Member of the Green River Formation are from Wyoming Oil and Gas Conservation Commission (2002).

meteoric waters through fracture systems in the Antrim Shale is purported to be the mechanism for transport of microbes and subsequent generation of biogenic gas (for example, see Schoell and others, 1997); natural fractures and well stimulation are also important to gas producibility (Curtis, 2002). A significant and perhaps critical difference between the Antrim Shale and Wilkins Peak accumulations may be the absence of produced water in Wilkins Peak wells when compared to the relatively abundant water (5–500 barrels/day) produced in Antrim Shale wells (Curtis, 2002; Wyoming Oil and Gas Conservation Commission, 2002), particularly if water is linked closely to biogenic gas generation. However, it is not known if the absence of water, the lack of well-developed fractures, or both, have played a role in the relatively low volumes of gas encountered in the Wilkins Peak to date. For this reason, comparison of the Wilkins Peak and Antrim Shale gas accumulations is only speculative at this point.

50370981: Wasatch–Green River Coalbed Gas Assessment Unit

The Wasatch–Green River Coalbed Gas Assessment Unit (fig. 10) includes areas where coal beds in the main body, and Red Desert and Niland Tongues of the Wasatch Formation, and the Luman Tongue of the Green River Formation (figs. 6 and 7) are present in outcrops and in the shallow (less than 2,500 ft) subsurface. The assessment unit boundary is generally defined by the outcrop extent of the Luman and Niland Tongues, although in the Red Desert Basin area (fig. 10), the boundary was extended to include areas of concentrated coal outcrops in the main body and Red Desert Tongue of the Wasatch Formation, based on studies of Masursky (1962) and Pipiringos (1961). Although minor, sporadic coal beds are present in the Wasatch Formation elsewhere in the CTPS, primary Eocene coal deposits are present in marginal lacustrine strata in the western Washakie Basin and central Great Divide Basin. Correspondingly, the assessment unit area is limited by the interpreted extent of these primary coal depocenters. The assessment unit includes a median estimated extent of about 665,000 acres (1,040 mi^2), and variability in the assessment unit area (minimum-median-maximum extent; Appendix A) relates primarily to uncertainty as to the limits of coal in the subsurface of the Washakie and Sand Wash Basins. This assessment unit is considered hypothetical because there has been no recorded production of coalbed gas from the Wasatch or Green River Formations.

In the Red Desert Basin area of the central Great Divide Basin (fig. 10), Masursky (1962) identified seven major coal zones within a 700-ft-thick coal-bearing interval in the main body of the Wasatch Formation (fig. 6). Coal beds were identified in outcrops and in shallow (less than 500 ft) drill holes. Lenticular coal beds as thick as 42 ft are present locally, with several beds as thick as 20 ft; most coal beds, however, average about 7 ft in thickness. In an adjacent study area to the west, Pipiringos (1961) identified 10 coal zones within an interval of about 1,000 ft in thickness (fig. 6) within the Red Desert, Niland, and Luman Tongues. About 30 coal beds were observed in outcrops, with coal beds ranging in thickness from a few inches to as much as 21 ft locally (Pipiringos, 1961). Analyses (as-received) of samples from thicker Eocene coal beds in the Great Divide Basin indicate an average moisture content of about 21 percent, an average ash yield of about 16 percent, an average total sulfur content of 2.5 percent, and an average heat-of-combustion value of about 7,900 Btu/lb (Glass, 1981, after Smith and others, 1972). Apparent coal rank varies from subbituminous C to B (Pipiringos, 1961; Masursky, 1962).

In the Vermillion Creek Basin area on the southeast flank of the Rock Springs uplift (fig. 10), coal beds are distributed within the main body and Niland Tongue of the Wasatch Formation, and in the Luman Tongue of the Green River Formation (fig. 7). In measured sections of the Niland Tongue in the Vermillion Creek Basin area, Roehler (1987) reports coal thickness typically ranging from a few inches to several feet. An exception to the generally thin and lenticular nature of coal beds in the Niland Tongue in this area is the Vermillion Creek coal bed, which is present throughout an area of 23 mi^2 and attains a maximum net coal thickness (excluding partings) of 12 ft locally (Ellis, 1987). The Vermillion Creek coal bed has an apparent rank of high-volatile C bituminous (Hatch, 1987), although inconsistent agglomerating characteristics in certain coal samples indicate the coal could also be considered as subbituminous (for example, see Ellis, 1987). As-received moisture values typically range from about 11 to 15 percent, and average, as-received values for ash yield and total sulfur content are 18.2 and 5.6 percent, respectively; heat-of-combustion values (moist, mineral-matter-free basis) average 11,556 Btu/lb (Ellis, 1987; Hatch; 1987).

Because no coalbed gas production or test data specific to the Wasatch and Green River Formations are available, coalbed gas wells producing from subbituminous coal in the Fort Union Formation in the Powder River Basin (PRB) in northeastern Wyoming were used as analogs for estimating the cell size and total recovery per cell for untested cells in the assessment unit (Appendix A). Reported gas contents for Fort Union Formation coal in the PRB can vary from 6 to more than 75 standard cubic ft/ton (scf/ton) and are commonly in the range of 20 to 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 Wasatch and Green River Formations are of similar rank (subbituminous), gas contents might also be similar. Powder River Basin wells used as analogs for estimated ultimate recovery (EUR) were restricted to gas wells producing from the 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 Wasatch–Green River Coalbed Gas Assessment Unit drew directly from cell sizes applied to coalbed-gas

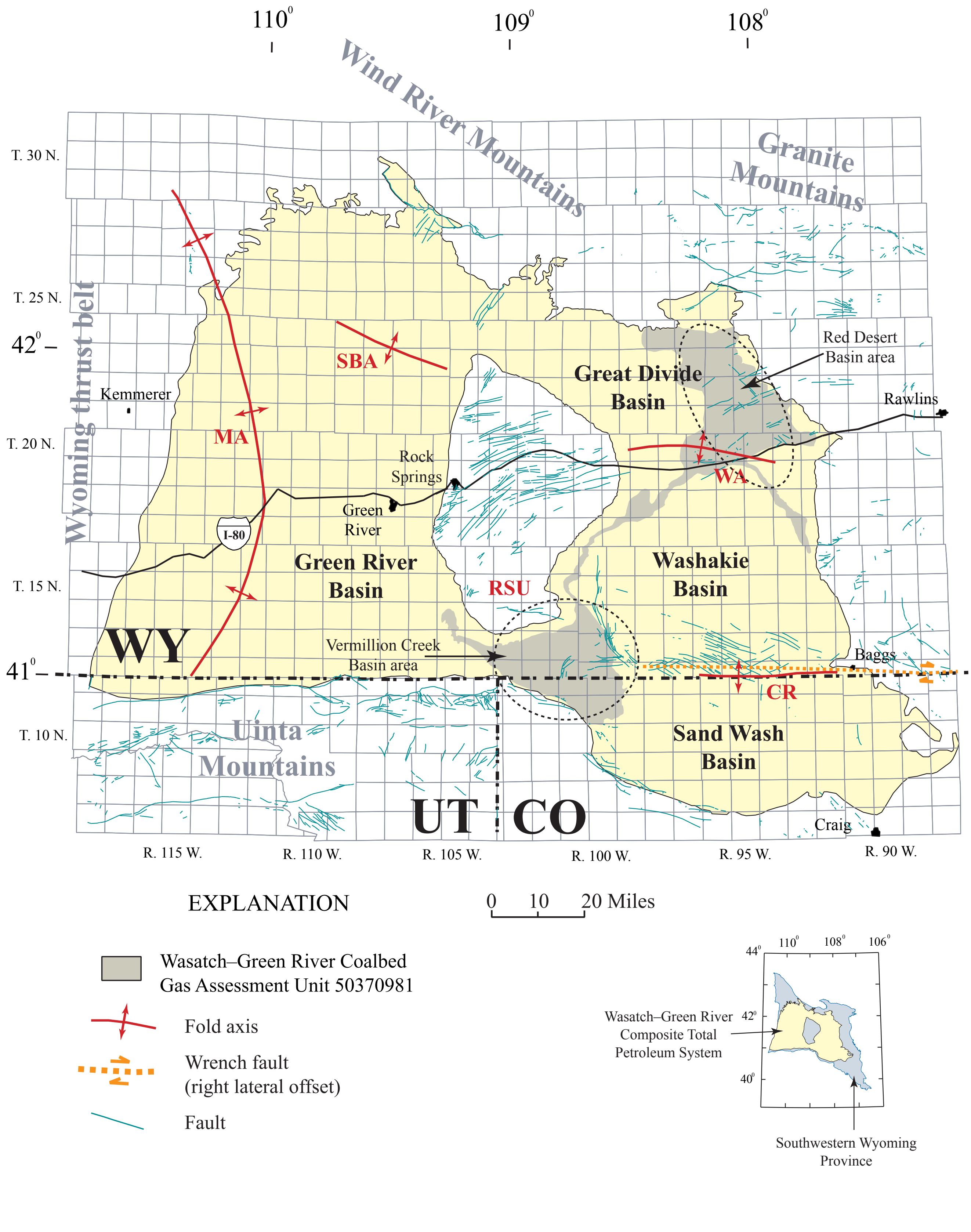


Figure 10. Boundary and extent of the Wasatch–Green River Coalbed Gas Assessment Unit (50370981) in the Wasatch–Green River Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. CR, Cherokee ridge; WA, Wamsutter arch; SBA, Sandy Bend arch; MA, Moxa arch; RSU, Rock Springs uplift.

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 A). A 40-acre cell size was used at the minimum because of strong evidence for interference between wells producing from fields with 20-acre spacing (Romeo Flores, U.S. Geological Survey, oral commun., 2003). Although some interference has been observed at 40-acre spacing, its occurrence is reduced. The 80-acre cell size applied to the median estimate is considered optimal in regard to gas volume and recovery, de-watering considerations, and reduction (or omission) of significant interference between adjacent wells. The maximum of 140 acres accounts for increased drainage areas in exceptionally continuous and permeable coal reservoirs.

Coal beds in the Wasatch and Green River are generally thinner than Anderson and Canyon coal bed analogs in the Powder River Basin, which range from about 20 to 30 ft in thickness. Wasatch and Green River coal beds are as thick as 42 ft locally (Masursky, 1962), but thicker coal beds such as this are rare, and many coal beds in the CTPS are less than 10 ft thick. Additionally, most of the thicker coals (20 ft or greater) are lenticular and might not encompass a significant geographic area. Although no direct correlation has been made between coal thickness, gas content, and enhanced production, greater coal volumes associated with thick, continuous coal beds should result in a greater volume of coal bed gas per unit area of land (for example, see Choate and others, 1984). Given the overall thin and lenticular nature of Wasatch and Green River coal, estimated ultimate recoveries anticipated for Wasatch–Green River coalbed gas wells might be less than EURs in Powder River Basin wells, particularly in terms of maximum levels. A minimum EUR of 0.02 BCFG was applied to untested cells in the assessment unit (Appendix A). 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 0.1 BCFG was applied to untested cells in the Wasatch–Green River Coalbed Gas Assessment Unit. 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), and because of the differences in coal thickness and continuity, a slightly lower median value was applied. The maximum EUR for untested cells is estimated at 0.8 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, U.S. Geological Survey, oral commun. 2002). Again, because of the anticipated differences in gas volume due to the lesser coal volume, a maximum EUR of 0.8 bcfg, which is less than both PRB analog EURs, was applied to untested cells in the Wasatch–Green River Coalbed Gas Assessment Unit.

Overall, the potential for significant coalbed gas production from the Wasatch and Green River Formations in the near future seems limited. The thin, discontinuous nature of these coal beds could restrict reservoir (and gas) volume, and the fact that many of the coal beds are in close proximity to outcrops could result in gas leakage. Estimates for the percentage of the untested assessment unit area with the potential for additions to reserves are a minimum of 1 percent, a median of 6 percent, and a maximum of 15 percent (Appendix A). The minimum value represents potential related solely to the Vermillion Creek coal bed in Vermillion Creek Basin (fig. 10) and includes areas where coal thickness generally ranges from 5 to 12 ft and overburden depths exceed about 200 ft (for example, see Ellis, 1987). The median estimate includes the Vermillion Creek Basin area, coupled with potential areas in parts of the central Great Divide Basin where coal bed thickness is estimated to exceed 10 ft or more. The maximum area includes the entire Vermillion Creek coal bed area (for example, see Ellis, 1987), where overburden exceeds about 100 ft, and areas of coal in the central Great Divide Basin (Pipiringos, 1961; Masursky, 1962), where overburden is estimated to be greater that 60 ft.

Assessment of Undiscovered Resources—Summary of Results

The total mean estimate of undiscovered coalbed-gas resources in the Wasatch–Green River Coalbed Gas Assessment Unit is 64.7 billion cubic feet of gas (BCFG). Tabulated estimates are listed in table 1. These estimates are based on concepts and methodology described in Schmoker (2003) and Crovelli (2003).

Table 1. Estimated undiscovered resources in the Wasatch–Green River 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**
Wasatch-Green River Composite TPS													
Wasatch-Green River Continuous Gas AU	***Gas***	Not quantitatively assessed											
Wasatch-Green River Coalbed Gas AU	***CBG***					27.80	58.40	122.60	64.70	0.00	0.00	0.00	0.00
Total continuous resources						**27.80**	**58.40**	**122.60**	**64.70**	**0.00**	**0.00**	**0.00**	**0.00**

References

Boreck, D.L., and Weaver, J.N., 1984, Coalbed methane study of the Anderson coal deposit, Johnson County, Wyoming—A preliminary report: U.S. Geological Survey Open-File Report 84–831, 16 p.

Bostick, N.H., Hatch, J.R., Daws, T.A., Love, A.H., Lubeck, Sister C.M., and Threlkeld, C.N., 1987, Organic geochemistry and organic petrography, *in* Roehler, H.W., and Martin, P.L., eds., Geological investigations of the Vermillion Creek coal bed in the Eocene Niland Tongue of the Wasatch Formation, Sweetwater County, Wyoming: U.S. Geological Survey Professional Paper 1314A–L, p. 133–163.

Bradley, W.H., 1964, Geology of Green River Formation and associated Eocene rocks in southwestern Wyoming and adjacent parts of Colorado and Utah: U.S. Geological Survey Professional Paper 496–A, 86 p.

Bradley, W.H., 1973, Oil shale formed in desert environment; Green River Formation, Wyoming: Geological Society of America Bulletin, v. 84, p. 1121–1124.

Carroll, A.R., and Bohacs, K.M., 2001, Lake-type controls on petroleum source rock potential in nonmarine basins: American Association of Petroleum Geologists Bulletin, v. 85, no. 6, p. 1033–1053.

Choate, Raoul, Johnson, C.A., and McCord, J.P., 1984, Geologic overview, coal deposits, and potential for methane recovery from coal beds—Powder River Basin, *in* Rightmire, C.T., Eddy, G.E., and Kirr, J.N., eds., Coalbed methane resources of the United States: American Association of Petroleum Geologists, Studies in Geology, series 17, p. 335–352.

Coleman, D.D., 2001, -70 per mil methane, is it biogenic or thermogenic?: American Association of Petroleum Geologists—2001 Annual Meeting Expanded Abstracts, Denver, Colo., June 3–6, 2001, v. 2001, p. 39.

Crovelli, R.A., 2003, Chapter 22, Analytical resource assessment method for continuous petroleum accumulations—The ACCESS assessment method, *in* USGS Uinta-Piceance Assessment Team, compilers, Petroleum systems and geologic assessment of oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–B, ver. 1.0, CD–ROM.

Culbertson, W.C., 1971, Stratigraphy of the trona deposits in the Green River Formation, southwest Wyoming: Laramie, Wyoming University Contributions to Geology, v. 10, p. 15–23.

Curtis, J.B., 2002, Fractured shale-gas systems: American Association of Petroleum Geologists Bulletin, v. 86, p. 1921–1938.

Dubiel, R.F., 2003, Geology, depositional models, and oil and gas assessment of the Green River total petroleum system, Uinta-Piceance Province, eastern Utah and western Colorado, *in* USGS Uinta-Piceance Assessment Team, compilers, Petroleum systems and geologic assessment of oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–B, version 1, CD–ROM.

Ellis, M.S., 1987, Coal resources, *in* Roehler, H.W., and Martin, P.L., eds., Geological investigations of the Vermillion Creek coal bed in the Eocene Niland Tongue of the Wasatch Formation, Sweetwater County, Wyoming: U.S. Geological Survey Professional Paper 1314A–L, p. 191–202.

Glass, G.B., 1981, Coal deposits of Wyoming, *in* Reid, S.G., and Miller, D.D., eds., Energy resources of Wyoming: Wyoming Geological Association Guidebook, 32nd Annual Field Conference, Jackson Hole, Wyo., September 20–22, 1981, p. 181–236.

Grabowski, G.J., Jr., and Bohacs, K.M., 1996, Controls on composition and distribution of lacustrine organic-rich rocks of the Green River Formation, Wyoming: American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, 1996 Annual Convention, San Diego, Calif., Annual Meeting Abstracts, v. 5, p. 55.

Green, G.N., 1992, The digital geologic map of Colorado in ARC/INFO format: U.S. Geological Survey Open-File Report 92–0507.

Green, G.N., and Drouillard, P.H., 1994, The digital geologic map of Wyoming in ARC/INFO format: U.S. Geological Survey Open-File Report 94–0425, 10 p.

Hatch, J.R., 1987, Element geochemistry, *in* Roehler, H.W., and Martin, P.L., eds., Geological investigations of the Vermillion Creek coal bed in the Eocene Niland Tongue of the Wasatch Formation, Sweetwater County, Wyoming: U.S. Geological Survey Professional Paper 1314A–L, p. 121–131.

Horsfield, Brian, Curry, D.J., Bohacs, K., Littke, R., Rullkotter, J., Schenk, H.J., Radke, M., Schaefer, R.G., Carroll, A.R., Isaksen, G., and Witte, E.G., 1994, Organic geochemistry of freshwater and alkaline lacustrine sediments in the Green River Formation of the Washakie Basin, Wyoming, U.S.A.: Organic Geochemistry, v. 22, no. 3–5, p. 415–440.

IHS Energy Group, 2001, [includes data current as of December, 2000] PI/Dwights Plus U.S. Production and Well Data: Englewood, Colo., database available from IHS Energy Group, 15 Inverness Way East, D205, Englewood, CO 80112, U.S.A.

Johnson, R.C., 1989, Geologic history and hydrocarbon potential of Late Cretaceous-age, low-permeability reservoirs, Piceance basin, western Colorado: U.S. Geological Survey Bulletin 1787–E, 51 p.

Law, B.E., 1984, Relationships of source-rock, thermal maturity, and overpressuring to gas generation and occurrence in low-permeability Upper Cretaceous and lower Tertiary rocks, Greater Green River Basin, Wyoming, Colorado, and Utah, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 469–490.

Law, B.E., 1996, Southwestern Wyoming Province (037), in Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS–30, release 2, CD–ROM publication.

Law, B.E., Spencer, C.W., Charpentier, R.R., Crovelli, R.A., Mast, R.F., Dolton, D.L., and Wandrey, C.J., 1989, Estimates of gas resources in overpressured low-permeability Cretaceous and Tertiary sandstone reservoirs, Greater Green River Basin, Wyoming, Colorado, and Utah, in Eisert, J.L., ed., Gas resources of Wyoming: Wyoming Geological Association, 40th Field Conference Guidebook, p. 39–61.

Levine, J.R., 1993, Chapter 3; Coalification—The evolution of coal as source rock and reservoir rock for oil and gas, *in* Law, B.E., and Rice, D.D., eds., Hydrocarbons from coal: American Association of Petroleum Geologists, Studies in Geology, no. 38, p. 39–78.

Magoon, L.B., and Dow, W.G., 1994, The petroleum system, *in* Magoon, L.B., and Dow, W.G., eds., The Petroleum System—From source to trap: American Association of Petroleum Geologists, AAPG Memoir 60, p. 3–24.

Martini, A.M., Budai, J.L., Walter, L.M., Ku, T., and Schoell, M., 1996, Geochemical constraints on microbial methanogenesis in an unconventional gas reservoir—Devonian Antrim Shale, MI: American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, 1996 Annual Meeting Abstracts, v. 5, p. 91–92.

Masursky, Harold, 1962, Uranium-bearing coal in the eastern part of the Red Desert area, Wyoming: U.S. Geological Survey Bulletin 1099–B, 152 p.

Meissner, F.F., 1984, Cretaceous and lower Tertiary coals as sources for gas accumulations in the Rocky Mountain area, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 401–431.

Pipiringos, G.N., 1961, Uranium-bearing coal in the central part of the Great Divide Basin: U.S. Geological Survey Bulletin 1099–A, 104 p.

Rice, D.D., 1993, Chapter 7—Composition and origins of coalbed gas, *in* Law, B.E., and Rice, D.D., eds., Hydrocarbons from coal: American Association of Petroleum Geologists, Studies in Geology, no. 38, p. 159–184.

Rightmire, C.T., 1984, Coalbed methane resource, *in* Rightmire, C.T., Eddy, G.E., and Kirr, J.N., eds., Coalbed methane resources of the United States: American Association of Petroleum Geologists, Studies in Geology Series, no. 17, p. 1–13.

Roehler, H.W., 1987, Structure and stratigraphy, *in* Roehler, H.W., and Martin, P.L., eds., Geological investigations of the Vermillion Creek coal bed in the Eocene Niland Tongue of the Wasatch Formation, Sweetwater County, Wyoming: U.S. Geological Survey Professional Paper 1314A–L, p. 13–23.

Roehler, H.W., 1992a, Description and correlation of Eocene rocks in stratigraphic reference sections for the Green River and Washakie Basins, southwest Wyoming: U.S. Geological Survey Professional Paper 1506–D, 83 p.

Roehler, H.W., 1992b, Correlation, composition, areal distribution, and thickness of Eocene stratigraphic units, Greater Green River Basin, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper 1506–E, 49 p.

Ruble, T.E., Lewan, M.D., and Philp, R.P., 2001, New insights on the Green River petroleum system in the Uinta Basin from hydrous pyrolysis experiments: American Association of Petroleum Geologists Bulletin, v. 85, no. 8, p. 1333–1371.

Schmoker, J.W., 1996, Method for assessing continuous-type (unconventional) hydrocarbon accumulations, *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS–30, CD–ROM.

Schmoker, J.W., 2003, Chapter 17, U.S. Geological Survey assessment concepts for continuous petroleum accumulations, *in* USGS Uinta-Piceance Assessment Team, compilers, Petroleum systems and geologic assessment of oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69–B, version 1.0, CD–ROM.

Schoell, Martin, Martini, A.M., and Walter, L.M., 1997, Microbial oxidation of gaseous hydrocarbons in reservoirs—Antrim Shale/Michigan Basin provides time constraints: American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, 1997 Annual Meeting, Dallas, Texas, Program with Abstracts, v. 6, p. 103.

Smith, J.B., Ayler, M.F., Knox, C.C., and Pollard, B.C., 1972, Strippable coal reserves of Wyoming—Location, tonnage, and characteristics of coal and overburden: U.S. Bureau of Mines Information Circular, no. 8538, 51 p.

Stricker, G.D., Flores, R.M., Ochs, A.M., and Stanton, R.W., 2000, Powder River Basin coalbed methane—The USGS role in investigating this ultimate clean coal by-production: Proceedings of the 25th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Fla., 2000, p. 695–708.

Sullivan, Raymond, 1985, Origin of lacustrine rocks of Wilkins Peak Member, Wyoming: American Association of Petroleum Geologists Bulletin, v. 69, p. 913–922.

Tegelaar, E.W., and Noble, R.A., 1994, Kinetics of hydrocarbon generation as a function of the molecular structure of kerogen as revealed by pyrolysis-gas chromatography: Organic Geochemistry, v. 22, p. 543–574.

Trudell, L.G., Roehler, H.W., and Smith, J.W., 1973, Geology of Eocene rocks and oil yields of Green River oil shales on part of Kinney Rim, Washakie Basin, Wyoming: U.S. Bureau of Mines Report of Investigations RI–7775, 151 p.

Wyoming Oil and Gas Conservation Commission (WOGCC), 2002, Web site, http://wogcc.state.wy.us, accessed 12–23–2002.

Appendix A. Basic input data form (part) for the Wasatch–Green River Coalbed Gas Assessment Unit (50370981), Wasatch–Green River CTPS, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. 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:.	Wasatch-Green River Composite	Number:	503709
Assessment Unit:……….	Wasatch-Green River Coalbed Gas	Number:	50370981
Based on Data as of:……			
Notes from Assessor…..	Analog: Anderson coals, Wasatch Formation Coalbed Gas in Powder River 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 598,000 median 665,000 maximum 731,000

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 6 maximum 15

Appendix A. Basic input data form (part) for the Wasatch–Green River Coalbed Gas Assessment Unit (50370981), Wasatch–Green River CTPS, Southwestern Wyoming Province, Wyoming, Colorado, and Utah. 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.

Wasatch-Green River Coalbed Gas, Assessment Unit 50370981 (cont.)

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	0.1	0.8

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)…………………………………….	60	200	400
Depth (m) of water (if applicable)………………			

Success ratios:	calculated mean	minimum	median	maximum
Future success ratio (%)........	41	20	40	70

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

Click here to return to
Volume Title Page