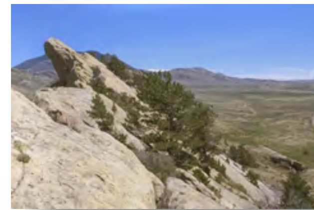
Chapter 5

Geologic Assessment of Undiscovered Oil and Gas Resources in the Mowry Composite Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah



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Volume Title Page

By Mark A. Kirschbaum and Laura N.R. Roberts

Chapter 5 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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By Mark A. Kirschbaum and Laura N.R. Roberts

Abstract

The Mowry Composite Total Petroleum System (TPS) encompasses the entire Southwestern Wyoming Province, which includes most of southwestern Wyoming and parts of northwestern Colorado and northeastern Utah. The TPS is a composite system because it contains petroleum generated from multiple source rocks including marine shale units of the Mowry and Thermopolis Shales and their equivalents and possibly contributions from marine shale of the Allen Hollow Shale Member of the Frontier Formation, and from coaly and lacustrine facies in continental units of the Bear River, Frontier, and Dakota Formations. Petroleum was generated during at least two separate tectonic events leading to (1) generation and migration of oil and gas at about 80–100 million years ago eastward out of a foredeep basin now preserved in the Idaho-Wyoming-Utah thrust belt, which forms the western border of the province; and (2) Cretaceous through present-day generation (80 million years ago to present) of petroleum from source rocks buried during Laramide basin development within the province. Oil and gas migrated into fluvial, tidal, deltaic, and shoreface sandstone reservoirs of the Bear River and Frontier, Cloverly, Dakota Sandstone Formations, and Muddy Sandstone Member of the Thermopolis Shale. The hydrocarbons were trapped in structural, stratigraphic, and basin-centered accumulations. Seals include thick, continuous marine shale and in some cases terrestrial to estuarine mudstone units, diagenetic seals, and capillary pressure seals.

A conventional oil and gas assessment unit and a continuous gas assessment unit (AU) were defined for the Mowry Composite TPS. The Mowry Conventional Oil and Gas AU covers the entire province and includes mainly intrabasinal and basin margin structures and stratigraphic traps and also includes traps located stratigraphically below the basin-centered accumulation of the Mowry Continuous Gas AU. The continuous gas AU underlies an area of about 11.5 million acres where the approximate limit of gas saturation is defined by (1) areas of overpressure, (2) bottom hole temperature greater than 200 degrees, (3) vitrinite reflectance greater than 0.8 percent, (4) low-permeability sandstones, and (5) no reported gas/water contacts in the reservoirs.

Mean resource estimates for the Mowry Conventional Oil and Gas AU totaled 6.6 million barrels of oil (MMBO), 0.2 trillion cubic feet of gas (TCFG), and 5.5 million barrels of natural gas liquids (MMBNGL). Mean resource estimates for the Mowry Continuous Gas AU are 8.5 TCFG and 171 MMBNGL. Total undiscovered gas resources for the continuous and conventional AUs having potential for production over the next 30 years are estimated at a mean of about 8.8 TCFG with a range from 6.8 to 10.9 TCFG.

Introduction

The purpose of this study is to assess the potential for undiscovered oil and gas resources in the Mowry Composite Total Petroleum System (TPS) in the Southwestern Wyoming Province. The TPS approach to resource assessment requires defining an area of active source rock and all known and undiscovered reservoirs and also requires an understanding of petroleum generation, trap formation, and seals, which are factors needed for oil and gas accumulations to exist (Magoon and Dow, 1994). The Mowry is a composite system because there are multiple source rocks present within about a 1,000-ft stratigraphic interval, and the relative contribution of petroleum from individual sources cannot be distinguished on the basis of data presently available. The name Mowry is applied to the TPS because it is by far the most important contributor to the petroleum system (Burtner and Warner, 1984). Two AUs were defined during this study, one conventional and one continuous.

The petroleum system approach used in this assessment is somewhat different from a play approach used for conventional accumulations in previous assessments (Law and others, 1989; Law, 1996), although the methodology is similar in both studies. Conventional accumulations of the Mowry TPS units were previously included in seven different plays (Law, 1996, Plays 3701–3707). These seven plays contained hydrocarbons from multiple source rocks, whereas the current approach combines all accumulations from Mowry composite source rocks together into one AU. The Mowry TPS continuous assessment unit can be compared very closely with the Cloverly-Frontier Play of the last assessment (Law 1996, Play 3740). In addition to the TPS approach, our current methodology employs a “sweet spot” analysis to refine the in-place volumetric calculations and play-scale technologically recoverable calculations used in previous assessments (Law and others, 1989; Law, 1996).

Acknowledgments

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Geologic History of Mowry Composite Total Petroleum System

The Southwestern Wyoming Province is an area bounded by major thrust faults or related structures and includes the Green River, Great Divide, Hoback, Sand Wash, and Washakie Basins (fig.1). The province also contains the Rock Springs uplift and four major intrabasinal anticlines: the Cherokee ridge, Moxa arch, Pinedale anticline, and Wamsutter arch (fig. 1). Sediments of the Mowry Composite TPS were deposited on the western edge of the Cretaceous Western Interior seaway in a foreland basin during Albian through Turonian time with a fold and thrust belt to the west active between Jurassic and latest Paleocene time (Jordan, 1981; Wiltschko and Dorr, 1983). Marine and terrestrial source rocks were buried within the foredeep and overridden by the eastward-breaking thrusts between approximately 100 and 80 million years ago (Ma) (Burtner and others, 1994) at which time petroleum was generated. Oil and gas migrated through carrier beds, such as the Oyster Ridge Sandstone Member of the Frontier Formation, and were trapped in stratigraphic pinch-outs or contemporaneous intrabasinal structures, such as the Moxa arch. By the Late Cretaceous and continuing into the Eocene, compressional tectonics created major basin-bounding structures of the Uinta and Wind River Mountains and lesser magnitude structures such as the Sparks Ranch thrust and Rawlins uplift (fig. 1). Subbasins and arches were created concurrently with these uplifts, which subdivide the province today. These basins were filled during Eocene to Miocene time with a thick succession of volcaniclastic sediments to at least an elevation surface about 4,000 ft above present-day topography (Mears, 1993). The total basin fill (Cretaceous to Eocene) buried the Mowry Composite TPS source rocks to a depth and thermal regime that allowed petroleum generation within the province resulting in continuous accumulations of oil and gas in the basin centers and parts of the Moxa arch and conventional accumulations where stratigraphic pinch-outs and structural traps were present at the margins of these subbasins—for example, the Rock Springs uplift. Erosion and dissection of the basins to present-day topography took place from the late Miocene to present (Mears, 1993).

Total Petroleum System

The total petroleum system (TPS) approach defines a mappable pod of active source rock, all known and undiscovered reservoirs, and the processes and mechanisms required for oil and gas accumulations to exist (Magoon and Dow, 1994). The Mowry Composite TPS is present within all of the Southwestern Wyoming Province (fig. 1) and extends westward to the approximate footwall cutoffs of strata against the Hogsback and Prospect thrusts (see cross sections by Lamerson, 1982). The Mowry Composite TPS is considered a composite system because there are multiple source rocks that could have generated petroleum mainly from Type-II and III organic matter in marine shales of the Mowry and Thermopolis Shales and their equivalents, and from Type-III, with minor contributions of Type-I organic matter from terrestrial facies of the Bear River and Frontier Formations and Dakota Sandstone (Burtner and Warner, 1984; Burtner and others, 1994) (fig. 2).

Reservoirs are sandstones in the Frontier Formation, Bear River Formation, Dakota Sandstone and equivalents, and the Muddy Sandstone Member of the Thermopolis Shale (fig. 2). Traps are stratigraphic, structural, and basin centered, and seals are diagenetic, capillary, or lithologic, including marine, estuarine, and terrestrial shale. There are AUs that extend over much of the Southwestern Wyoming Province: one is a basin-centered (continuous) accumulation (AU 261) and the other is conventional (AU 201).

Source Rock

Cretaceous shales are thought to be the source of much of the petroleum found in reservoirs of the Dakota Sandstone and Frontier Formation (Warner, 1982; Burtner and Warner, 1984). Oil produced from the Dakota in the Bridger Lake field (fig. 3) has saturated hydrocarbon distributions similar to oils derived from other Cretaceous source rocks in Rocky Mountain basins (Law and Clayton, 1987). In the Tip Top field on the northern Moxa arch (fig. 3), liquids produced from the Frontier are thought to have a Cretaceous source based

Figure 1. Mowry Composite Total Petroleum System (TPS) showing the pod of active source rock, producing wells, the line of cross section A–A', and major structural elements.

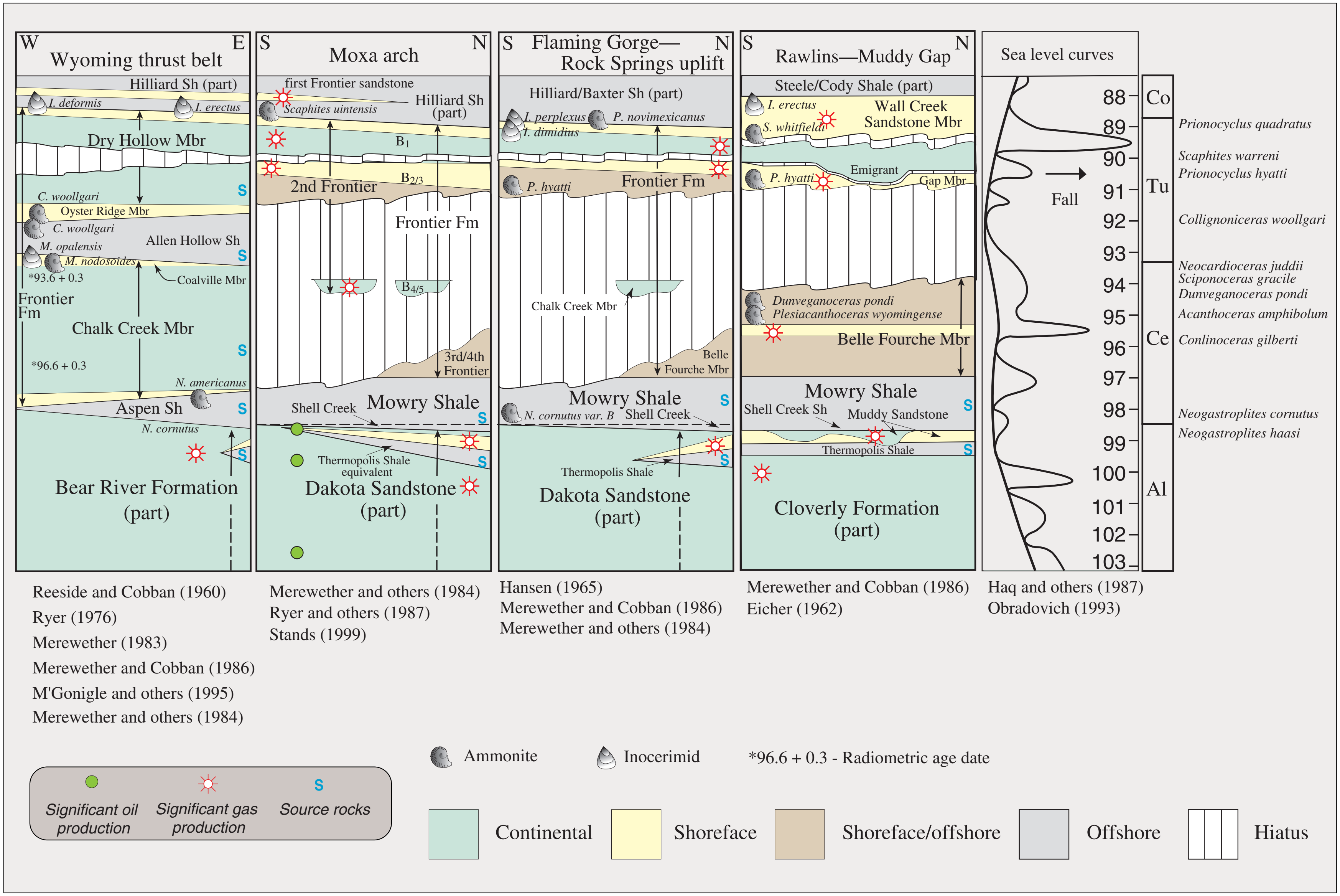


Figure 2. Diagrammatic columnar sections of the Mowry Composite Total Petroleum System for three locations within the Southwestern Wyoming Province and one for the Wyoming thrust belt located west of the province. Generalized depositional environments, significant fossils, significant oil and gas producing units, and potential source rocks are shown. The columns show stratigraphic names from outcrops. Subsurface equivalent names are shown for the Moxa arch area; B1–B5 are benches within the second Frontier. [Abbreviations: Sh, shale; Mbr, member; Al, Albian; Ce, Cenomanian; Tu, Turonian; Co, Coniacian]

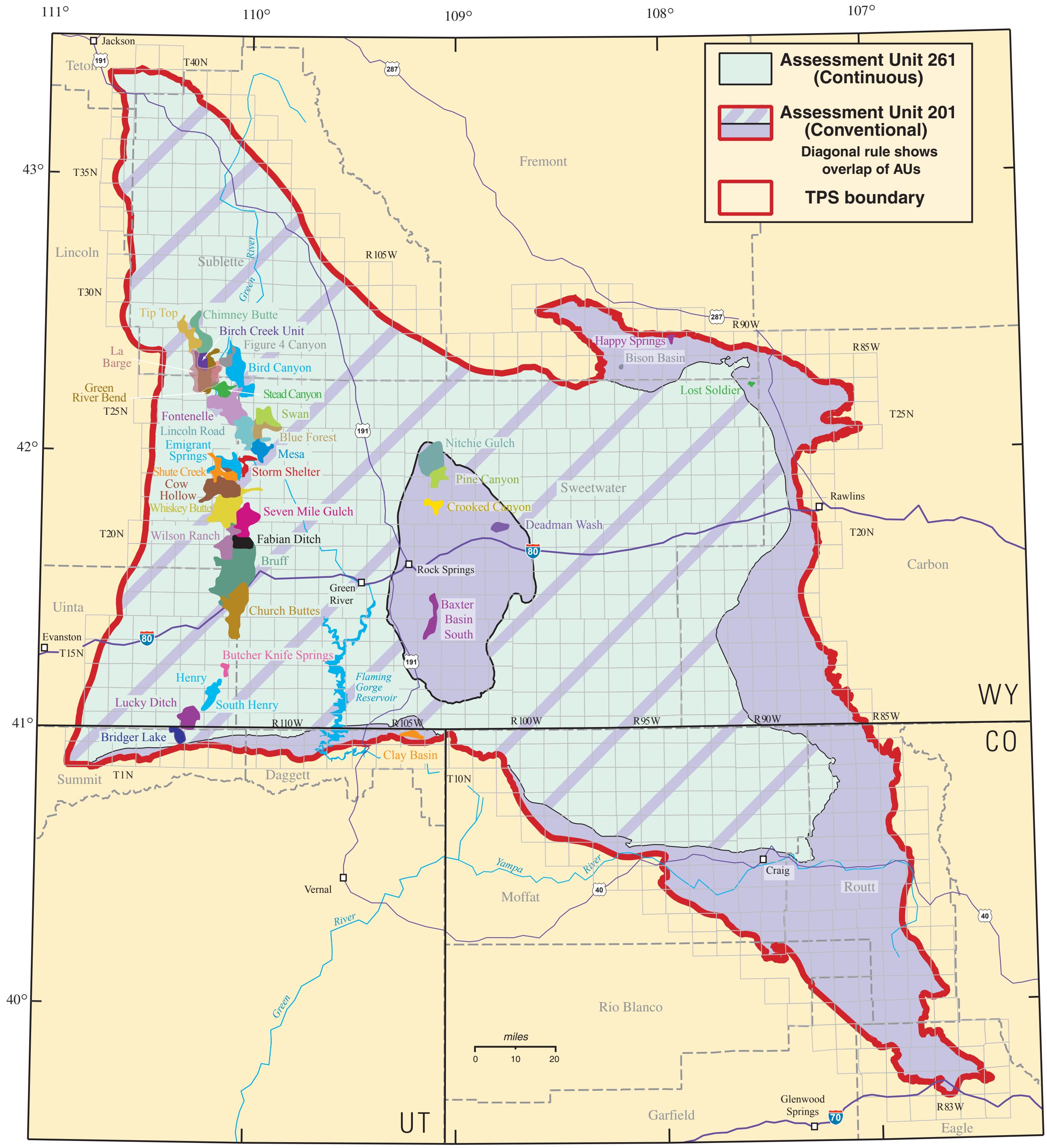


Figure 3. Map of the Mowry Composite TPS showing boundaries of the two assessment units and selected gas fields that produce from units of the TPS. Note that the Mowry Conventional Oil and Gas AU covers the entire TPS. The Mowry Continuous Gas AU overlaps the conventional AU. Colored lettering corresponds to respective field.

on pristane/phytane ratios (Edman and Cook, 1992, p. 19). Hydrocarbons have not been directly typed back to the Mowry, but the Mowry/Aspen is the Cretaceous shale with the highest content of total organic matter (Burtner and Warner, 1984) and is thought to be the dominant contributor of petroleum (Burtner and Warner, 1984; Law and Clayton, 1987). Other possible source rocks in the Mowry Composite Total Petroleum System are marine shales of the Allen Hollow and Thermopolis Shales and Bear River Formation and coals and carbonaceous shale in the Frontier and Bear River Formations and Dakota Sandstone. Type-II and III organic matter and minor amounts of Type-I organic matter are present in these strata (Burtner and others, 1994, p. 1620). Total organic carbon (TOC) extracted from 19 samples of the Mowry Shale in the Green River Basin ranges between 1.2 and 2.5 percent, anomalously low according to Burtner and Warner (1984) who believe the anomaly is due to the expulsion of carbon dioxide and hydrocarbons from the source rock.

In the province, the Mowry consists of laminated and bioturbated organic-rich mudrock (Byers and Larson, 1979). High resistivity values indicated on geophysical logs measured throughout the Mowry generally correspond to siliceous shales while low resistivity values (and high gamma values) can be related to bentonites (Nixon, 1973). The shale is siliceous due to the presence of abundant radiolarians that favored the cool waters of the restricted boreal Mowry sea (Davis, 1970). The silica was originally provided from volcanic sources near the Idaho batholith (Davis, 1970). This high-resistivity, organic-rich siliceous shale was deposited on an anoxic sea floor (Byers and Larson, 1979; Burtner and Warner, 1984). The anoxic condition of the Mowry sea not only preserved the radiolarian tests but preserved organic matter as well. The laminated mudrock grades upward and landward (westward) into bioturbated mudstone and sandstone, indicating more oxic conditions, shallower water, and proximity to the clastic source area (Burtner and Warner, 1984).

Coals and carbonaceous shales in the Frontier, Dakota, and Bear River most likely contributed gas following burial and maturation. Thicker coals in the Frontier, which are presently restricted to the western thrust belt, attained maturity as early as the Late Cretaceous (Valenti, 1987). Coals of the Frontier reach a maximum reported thickness of 24 ft and are present in as many as nine separate seams (Weaver and M'Gonigle, 1987).

Maturation

The source rocks of the Mowry Composite TPS are mature over much of the province except where vitrinite reflectance values (R_o) are less than 0.6 percent at the basin margins and within the interior of the basin at the Rock Springs uplift (fig. 4). Mature source rocks are also present in parts of the upper plates of the western Wyoming thrusts (Burtner and others, 1994), and maturities as high as 2.01 percent R_o have been recorded from the Bear River Formation in the northern thrust belt (Wallem and others, 1981).

The Mowry has sufficient TOC and level of maturity to have provided an early Late Cretaceous (100–80 Ma) pulse of petroleum generation prior to the development of the Hogsback and Prospect thrusts (figs. 5A and B). The Mowry was buried in a rapidly subsiding foreland basin due to tectonic loading associated with the more westward Meade-Crawford thrusts (Burtner and others, 1994). Presumably, coals and carbonaceous shale in the Frontier, and perhaps the Bear River Formation and Dakota Sandstone, also generated petroleum early in the development of this petroleum system. Another period of generation may have taken place between 70 and 60 Ma following burial of the foredeep deposits beneath the Absaroka thrust (see Warner, 1982; Reisser and Blanke, 1989; Burtner and others, 1994).

One-dimensional modeling of burial history and thermal maturity was performed for seven well locations within the province east of the Wyoming thrusts, to determine thermal maturity and timing of petroleum generation (figs. 5B and C) (Roberts and others, Chapter 3, this CD–ROM). The start of oil generation for the Mowry Shale, a mix of Type-II and Type-III kerogen, occurred as early as 70 Ma in the deepest part of the province (Adobe Town location, fig. 5B). Oil generation started at about 46 Ma on the Moxa arch (Bruff 2 location, fig. 5B), which is consistent with the work of Dutton and Hamlin (1992) who thought these source rocks passed through the oil window at about 45 Ma at the earliest on the Moxa arch. Oil generation ended at all locations by about 43 Ma except on the Moxa arch. In the deepest parts of the province at the Adobe Town, Eagles Nest, and Wagon Wheel locations (fig. 5B), the generation of gas from the cracking of oil began at about 56 Ma, within about 6 m.y. of the end of oil generation. Gas generation from oil cracking ended at these deep locations by 41 Ma. Gas-prone source rocks of the Mowry (those containing predominantly Type-III kerogen), which were modeled only for those locations west of the Rock Springs uplift (fig. 5B), began generating gas at about 78 Ma. Gas generation from the Mowry has reached a peak at all locations but has ended only at Wagon Wheel.

Reisser and Blanke (1989) suggest a higher convective heat flow on the highest parts of the Moxa arch (for example Church Buttes/Bruff fields, fig. 3) and further suggest that thermal alteration of the oil accounts for observed variation in gas to oil ratios. They think liquid hydrocarbons are more likely to be found in the chilled thermal margins along the Uinta Mountains or in stratigraphic traps off the east flank of the Moxa arch, for example Swan field (Reisser and Blanke, 1989, their fig. 16).

Migration Summary

Migration of petroleum from source rocks of the Mowry Composite Total Petroleum System may have been two-phase

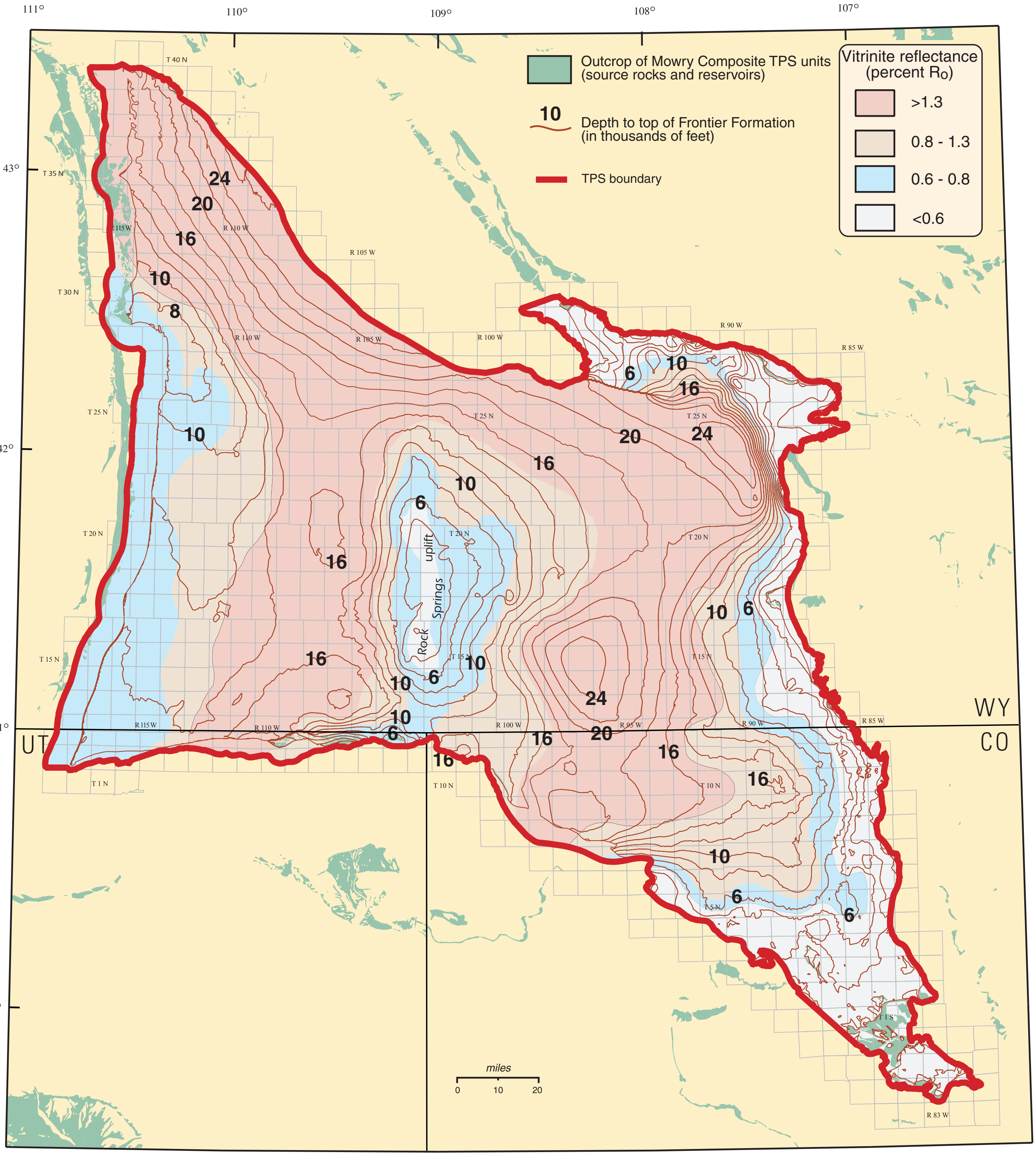
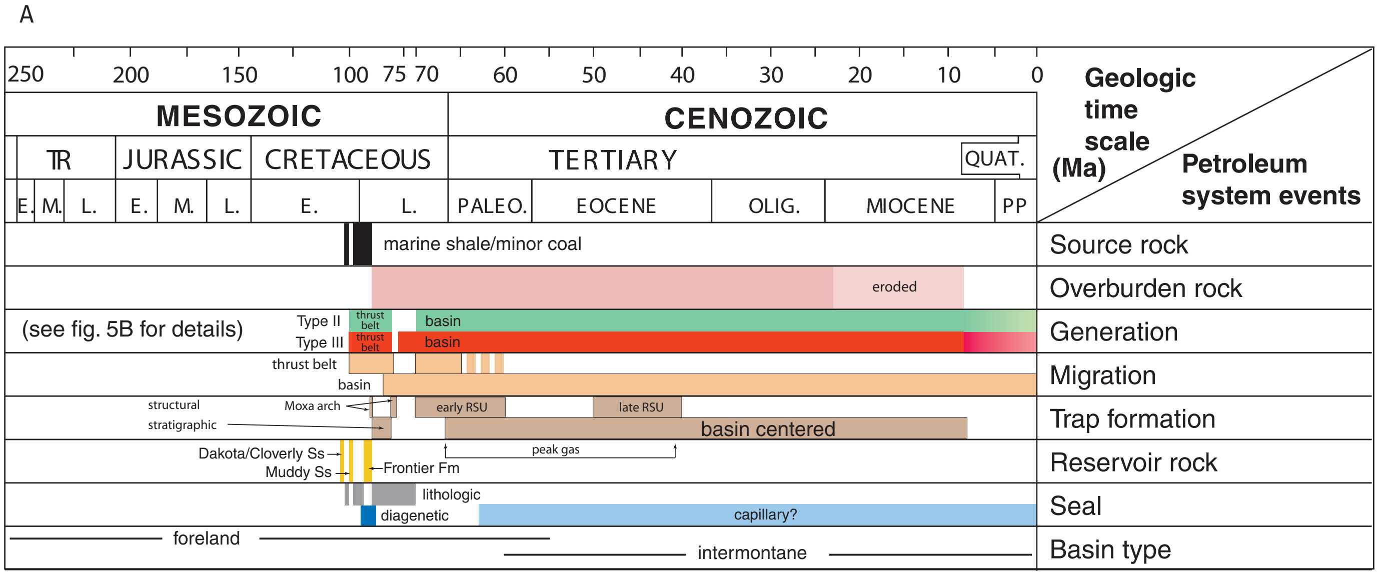
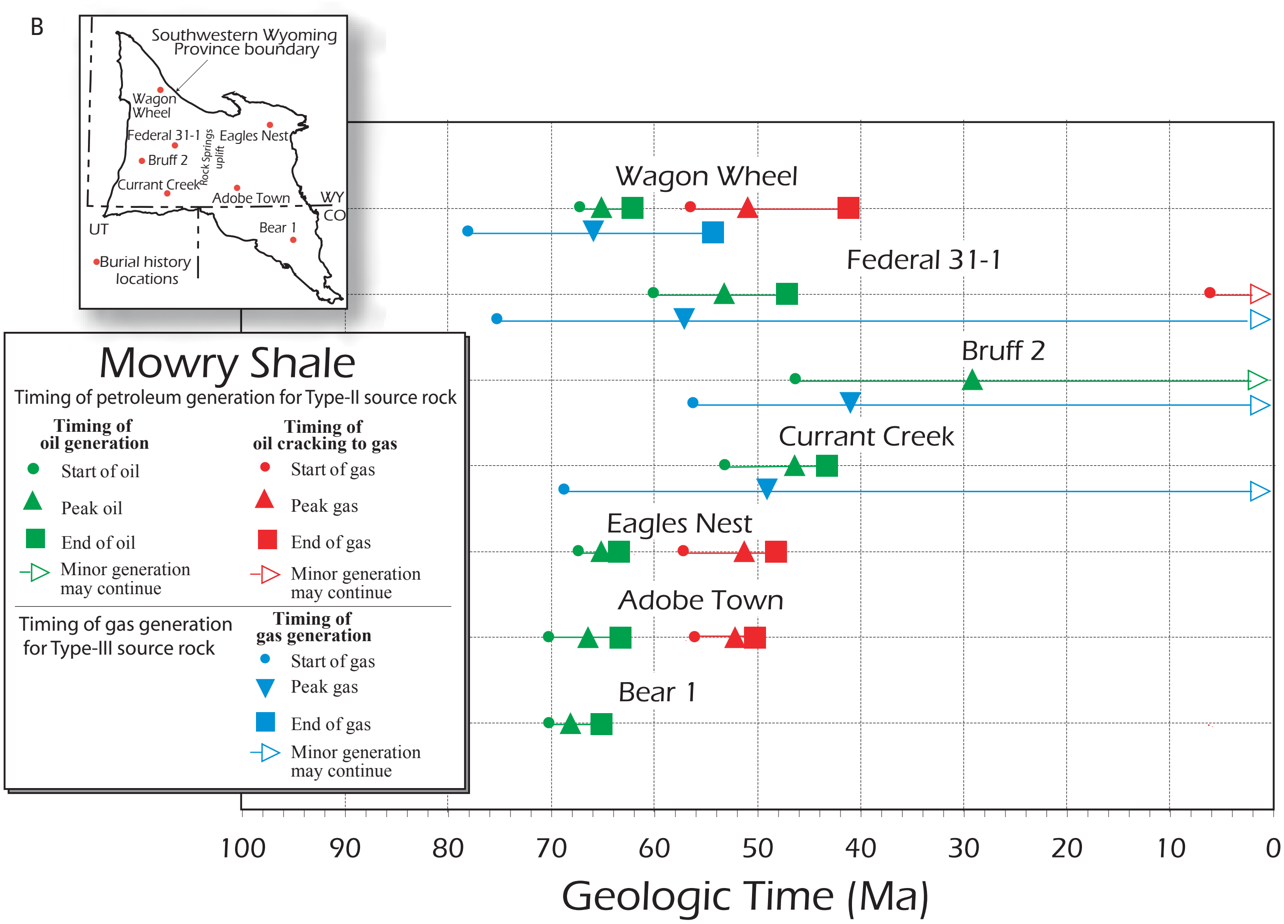


Figure 4. Extent of the Mowry Composite Total Petroleum System. Contours show depth to top of the Frontier Formation in thousands of feet using a 2,000-foot contour interval. Ranges of thermal maturity values (in percent R_o) at the top of the Frontier are indicated by colors.





Figures 5A, B. A, Petroleum system events chart for the Mowry Continuous and Conventional Assessment Units [Abbreviations: E, Early; M, Middle; L, Late; TR, Triassic; Paleo., Paleocene; Olig., Oligocene; PP, Pliocene/Pleistocene; RSU, Rock Springs uplift; Ss, Sandstone]. B, Timing of petroleum generation for Type-II and Type-III source rocks of the Mowry Shale in the Southwest Wyoming Province (from Roberts and others, Chapter 3, this CD–ROM). [Abbreviations: P, Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pg, Paleogene; Ng, Neogene]

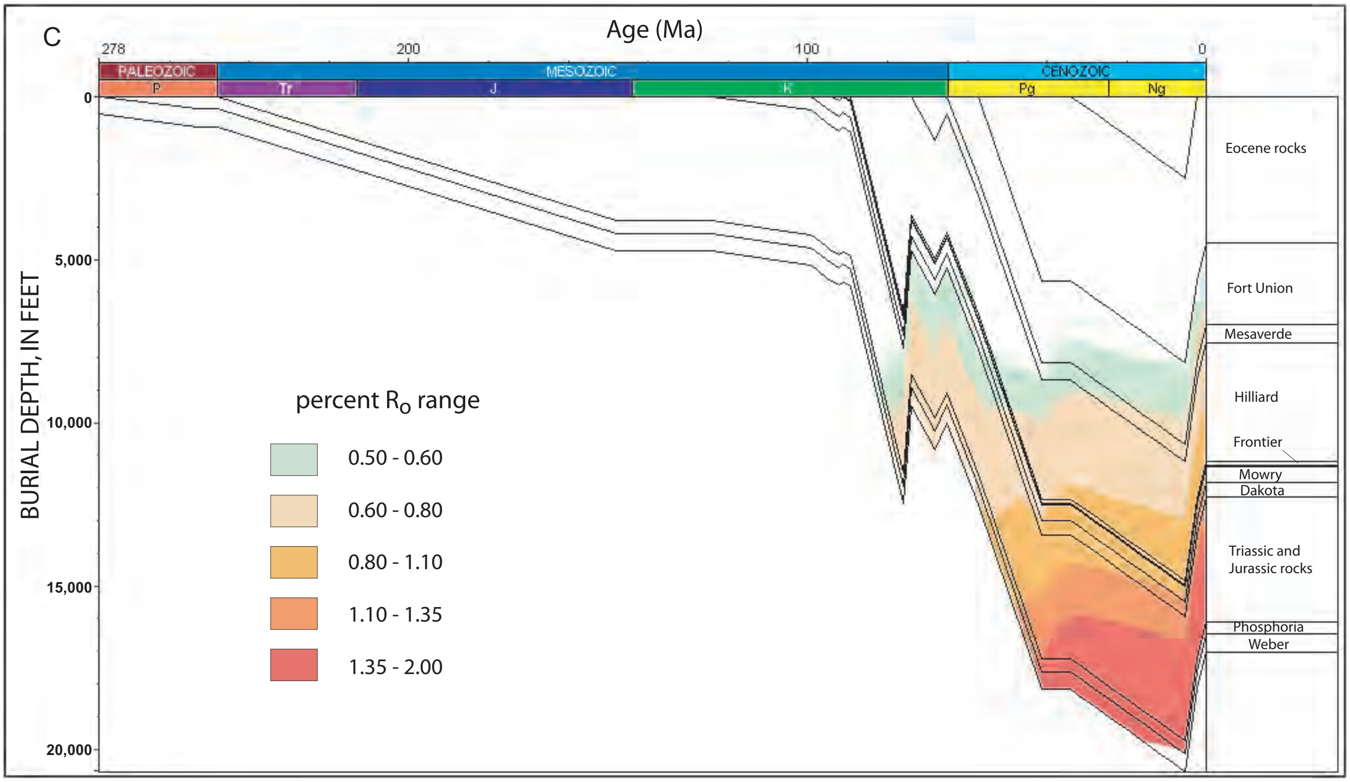


Figure 5C. C, Burial-history plot for the Bruff 2 well on the Moxa arch showing calculated ranges of vitrinite reflectance values in percent R_o (from Roberts and others, Chapter 3, this CD–ROM). [Abbreviations: P, Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pg, Paleogene; Ng, Neogene]

or perhaps continuous and consisted of lateral, vertical, and localized migration. Early lateral migration of petroleum generated between 100 and 80 Ma in what is now the overthrust belt took place before most of the major intrabasinal structures had formed in the province. The continuous Oyster Ridge Sandstone (2d bench of second Frontier, fig. 6) could have acted as a carrier bed and allowed the migration of gas eastward into the basin, perhaps even into stratigraphic traps east of the Rock Springs uplift. Migration of oil and gas into fluvial reservoirs of the Dakota is interpreted at about 70 Ma following emplacement of the Absaroka thrust (Reisser and Blanke, 1989). Vertical migration took place from about 55 Ma until present after most of the large Laramide structures, like the Rock Springs uplift were already developed. Migration of gas in sufficient volumes to displace interstitial water in areas such as the marginally mature La Barge platform is indicated from the low water yields, variable gas/water contacts, low permeability, and overpressured reservoirs (Webel, 1979; Edman and Cook, 1992). In-place generation, localized migration, and trapping took place within the basin centers.

Dutton and Hamlin (1992) showed that most of the Mowry had not passed through the gas window on the Moxa arch and thought that gas was generated from the deep basin and migrated into the Frontier about 43 Ma. Burial-history plots conducted during this study (Roberts and others, Chapter 3, this CD–ROM) also show similar patterns of thermal history for the Moxa arch (fig. 5C). Burial-history plots do not show the oil cracking to gas on the Moxa, and API gravities from all fields range between 33 and 60 degrees (light oil to condensate) (Cardinal and Stewart, 1979; Miller and others, 1992). Burtner and Warner (1984) show distinct Type-III, gas-prone source rock in many areas of the Greater Green River Basin. Light oil and condensate now reservoired in the Frontier may have been expelled from any Type-II kerogen present in the Mowry on the Moxa arch or the thrust belt during an earlier period of migration.

Reservoir Rocks

Reservoirs in the province can be divided into two groups of rocks separated by the Mowry Shale: the lower group is almost entirely Early Cretaceous and consists of the Dakota and Muddy Sandstones and equivalents; the upper group is Late Cretaceous and consists of the Frontier Formation (figs. 2 and 6).

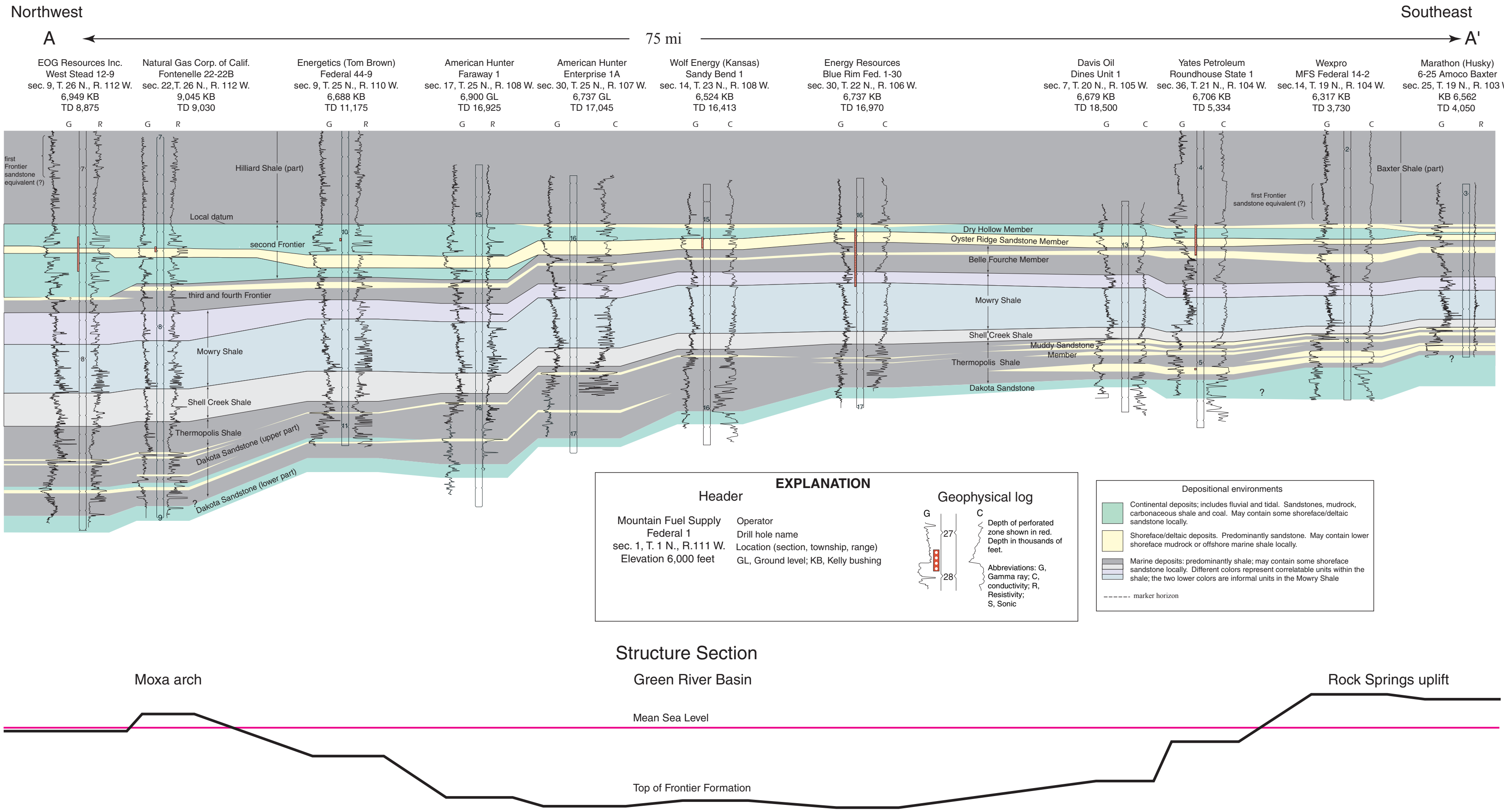


Figure 6. Stratigraphic cross section of the Mowry Composite TPS units from the overthrust belt, across the Moxa arch, to the Rock Springs uplift. A more detailed version of this cross section is shown in Kirschbaum and Roberts, Chapter 15, this CD–ROM. Line of section shown in figure 1. Datum is the first significant flooding surface above sandstones in the Frontier.

Dakota and Muddy Sandstones and Equivalents

The Dakota Sandstone consists of two informal members, lower and upper (Ryer and others, 1987), in the southern part of the Moxa arch and interfingers, in part, with the Thermopolis Shale to the north. The lower member of the Dakota is about 100–210 ft thick on the Moxa arch, intertongues with the Thermopolis Shale and changes nomenclature into the lower part of the Bear River Formation to the west and into the Cloverly Formation to the northeast (fig. 2) (Ryer and others, 1987). The upper member of the Dakota is as thick as 275 ft in the northern part of the Moxa arch (Ryer and others, 1987) and can be correlated with the upper part of the Bear River Formation to the west and with the Muddy Sandstone to the northeast (fig. 2).

Reservoirs in the Dakota and Muddy Sandstones and equivalent strata in the Bear River Formation consist of fluvial, estuarine, and nearshore marine sandstones. The fluvial systems were sourced from the south, fed a generally east-west oriented shoreline, and prograded over much of the province before being transgressed by the Thermopolis Shale (Ryer and others, 1987). Subsequent progradation and incision during deposition of the Muddy Sandstone also extended northward, encompassing a large part of the province before being transgressed by Mowry Shale. The Muddy consists of coarsening-upward and fining-upward successions deposited over the Thermopolis Shale. To the west on the Moxa arch, the Muddy consists of silty beds but grades into coarsening-upward successions of the Bear River Formation just west of the province boundary. The coarsening-upward successions are replaced in the northeastern part of the province by fining-upward successions, which have been interpreted as valley-fill deposits (Dolson and others, 1991).

Dakota reservoirs on the south part of the Moxa arch are conventional oil accumulations. Reservoirs produce from depths as great as about 17,700 ft (IHS Energy Group, 2001). The reservoirs have distinct gas or oil/water contacts and have higher permeabilities than the Dakota or Bear River in the northern Moxa arch. Dakota/Muddy sandstone porosity has a range of 8–23 percent and permeability of 0.06–750 millidarcies (mD) (Cardinal and Stewart, 1979; Miller and others, 1992). Sandstones are dominantly sublitharenites, but minor quartz arenites, subarkoses, and litharenites are also present (Muller and Coalson, 1989, their fig. 5). Fields in the Moxa/La Barge area produce much less water than southern Moxa arch fields. Some of these Dakota reservoirs have low permeabilities, such as at Seven Mile Gulch field (fig. 3) where the permeability is as low as 0.06 mD and are thought to be part of regional accumulations (Morton, 1992a). The northernmost reported gas/water contact is in Church Buttes field (fig. 3) (Curry, 1992); farther north in the Whiskey Butte and Seven Mile Gulch fields the gas column is reported to be part of a regional accumulation (Morton, 1992a and b). The fields in between (primarily Fabian Ditch and Bruff) show some evidence to support a conventional rather than continuous type of accumulation. In this study, Bruff field is considered to be the northernmost conventional accumulation in the Dakota/Muddy/Bear River interval. Along the arch, the mode of deposition changes from primarily fluvial in the south to primarily shoreface in the north (Ryer and others, 1987). It is possible that both types of accumulation exist here, with conventional reservoirs associated with the fluvial facies and continuous reservoirs present within the shoreface facies.

Frontier Formation

On outcrop just west of the Province boundary, the Frontier Formation consists of five members (fig. 2): in ascending order, the Chalk Creek, Coalville, Allen Hollow, Oyster Ridge, and Dry Hollow Members (Hale, 1960; M'Gonigle and others, 1995). These members are exposed on the hanging walls of imbricate thrusts in western Wyoming and northern Utah (fig. 1). In the subsurface, the Frontier is informally divided into the first through fourth Frontier. The second Frontier is further divided into benches 1–5 (fig. 2, Moxa arch column). The first and second Frontier sandstones are the main reservoirs (fig. 2). Total thickness of the formation on the hanging wall is over 1,000 ft, and these units thin into the province to about 250 ft thick in the footwall of the Hogsback thrust. The rapid thinning of the members is partly due to shortening of the section because of thrusting and subsequent erosion of strata of intermediate thickness from the hanging wall and partly due to thinning associated with decreasing accommodation space within the foreland basin. On the Moxa arch and Rock Springs uplift, remnants of the Chalk Creek Member are interpreted on well logs (fig. 6) and in core. The Oyster Ridge is easily traced from outcrop, where the unit is dated by the presence of *Collignoniceras woollgari*, into the subsurface to the western flank of the Rock Springs uplift and then back to outcrop near Flaming Gorge where the unit contains the ammonite *Prionocyclus hyatti*. The Dry Hollow Member can also be interpreted in the subsurface and traced as far as the Rock Springs uplift.

On the northeast margin of the province, the Frontier is about 600–1,000 ft thick and is divided into three members: in ascending order, the Belle Fourche, the Emigrant Gap (formerly called the unnamed member), and the Wall Creek (Merewether, 1983; Mieras, 1993). A correlation diagram (fig. 2) shows the age control and interpretations of the physical correlation of the units within the Southwestern Wyoming Province. The Belle Fourche Member approximately correlates to the Chalk Creek Member, the Emigrant Gap Member to the Oyster Ridge Member, and the Dry Hollow Member, in part, to the Wall Creek Member. Others have made this correlation as well (for example, Merewether and Cobban, 1986).

The main reservoirs in the Frontier are shoreface/deltaic, estuarine, and fluvial sandstones at depths down to about 19,950 ft (IHS Energy Group, 2001). Sandstones are mainly sublitharenites and litharenites with relatively minor amounts of feldspathic litharenites and lithic arkoses (Dutton and others, 1992, their fig. 33). Fluvial facies are more lithic-rich

(Winn and Smithwick, 1980). Within the province, sandstone porosity has a range of 2.4–28 percent and permeability has a range of 0.0008–500 mD (Cardinal and Stewart, 1979; Miller and others, 1992). In the Moxa arch area, tidal, fluvial, and shoreface sandstones have similar porosity ranging from an average of 9.3 to 11 percent (Winn and others, 1984; Stonecipher and Diedrich, 1993). Porosity is as much as about 17 percent and permeability is as much as 50 mD, with most measurements less than 2 mD for tidal and fluvial sandstones on the Moxa arch (Stonecipher and Diedrich, 1993). The fluvial and tidally influenced sandstones tend to be better quality reservoirs than shoreface sandstones because of early quartz cementation in the shoreface sandstones and dissolution of late calcite cements in fluvial/tidal sandstones (Winn and others, 1984). Lower shoreface sandstones have the lowest quality because of compaction and clay cementation (Dutton and others, 1992; Stonecipher and others, 1984). Frontier reservoirs produce from 123 named fields in the province, and the fields that rank highest in terms of number of producing wells (more than 100 wells) are Bruff, Church Buttes, Fontenelle, Green River Bend, Lincoln Road, Tip Top, and Whiskey Buttes (IHS Energy Group, 2001).

Traps/Seals

Production from conventional accumulations of the Mowry Composite TPS is from anticlines, fault-bounded closures, stratigraphic traps, or combinations of the three (Cardinal and Stewart, 1979; Miller and others, 1992). The most important structure influencing conventional accumulation is the Rock Springs uplift, which had minor expression during the latest Cretaceous and earliest Paleocene (Kirschbaum and Nelson, 1988) and major expression by latest Eocene and possibly Oligocene time. The Moxa arch also shows evidence of recurrent movement and initially may have provided structures for conventional accumulations, some of which were later modified or partially modified into continuous accumulations. Production from continuous (unconventional) accumulations is concentrated on the Moxa arch, presumably associated with intense fracturing and minor faulting on the structure (see Dutton and others, 1992; Anderson and Dietz, 2003) although depositional environment and diagenetic history are also important controls on reservoir quality (for example see Stonecipher and others, 1984; Stonecipher and Diedrich, 1993).

Major seals are provided by marine shale units of the Thermopolis, Mowry/Aspen, and Hilliard Shales (figs. 2 and 5A). Locally, seals are provided by mudrock deposited in coastal- or alluvial-plain settings. Diagenetic permeability barriers can act as seals or traps in some fields (Muller and Coalson, 1989; Reisser and Blanke, 1989). Diagenetic traps are described for Dakota reservoirs on the southern Moxa arch (Reisser and Blanke, 1989), and some workers think these traps also control production on the Moxa arch within the Frontier (Stands, 1999). Early clay cementation in upper Dakota fluvial channels sealed the reservoirs in the lower Dakota during early migration of petroleum (Muller and Coalson, 1989). These diagenetic seals were sufficient to preserve the integrity of the reservoirs during subsequent structural movement of the Moxa arch when the reservoirs might have been breached, allowing remigration of the petroleum (Reisser and Blanke, 1989). Diagenetic seals can also act as localized permeability barriers (for example, at Tip Top field, Edman and Cook, 1992). Capillary pressure seals associated with the development of basin-centered accumulations usually are created at the time of peak gas generation (Law and Dickinson, 1985).

Resource Assessment

The Mowry Composite Total Petroleum System consists of two assessment units (AU): AU 50370201 is conventional and covers all of the Southwestern Wyoming Province, and AU 50370261 is continuous and covers about 11,500,000 acres of the province (fig. 3).

Mowry Conventional Oil and Gas Assessment Unit (AU 50370201)

This assessment unit, which covers the entire area of the TPS, contains conventional structural and stratigraphic traps at or near normal hydrostatic reservoir pressures. The reservoirs generally have permeabilities greater than 1 mD and have oil/water or gas/water contacts.

Historically, 11 conventional oil fields and 29 conventional gas fields have been found in the province (NRG Associates, 2001) above the minimum accumulation size considered in this study of 0.5 million barrels of oil (MMBO) or 0.3 billion cubic feet of gas (BCFG). Oil accumulations range in size from about 0.65 to 40 MMBO (fig. 7) and gas accumulations range in size from about 3 to 900 BCFG (fig. 8). No conventional accumulations above the minimum size cutoff have been discovered since the mid-1980s.

The areas that have potential for additions to reserves in the next 30 years are estimated to contain relatively small fields located mainly in compartments having local structural closure or in small stratigraphic traps within the Rock Springs uplift, such as Deadman Wash field (fig. 3). Reservoir targets are fluvial sandstones in the Frontier, Dakota, or Muddy sandstones, shoreface sandstones in the Frontier, and possibly lowstand deltaic sandstones of the Frontier east of the Rock Springs uplift. Based on plots of size relative to discovery time (figs. 7 and 8), we estimate a median number of 3 undiscovered oil accumulations and 14 undiscovered gas accumulations that have the potential to be discovered in the next 30 years with a median size of 1.5 MMBO and a median of 12 BCFG, respectively (Appendix A).

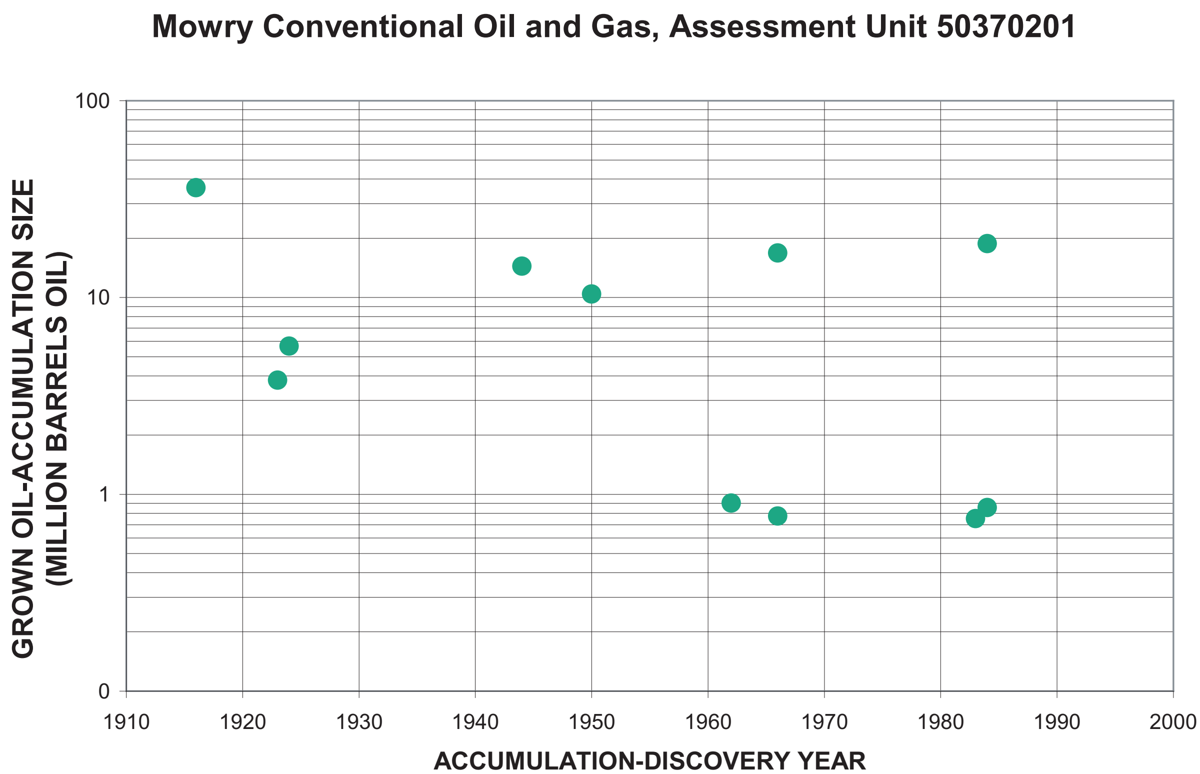


Figure 7. Plot showing size of grown oil accumulations (fields) relative to the discovery year for the Mowry Conventional Oil and Gas Assessment Unit 50370201. Data from NRG Associates (2001).

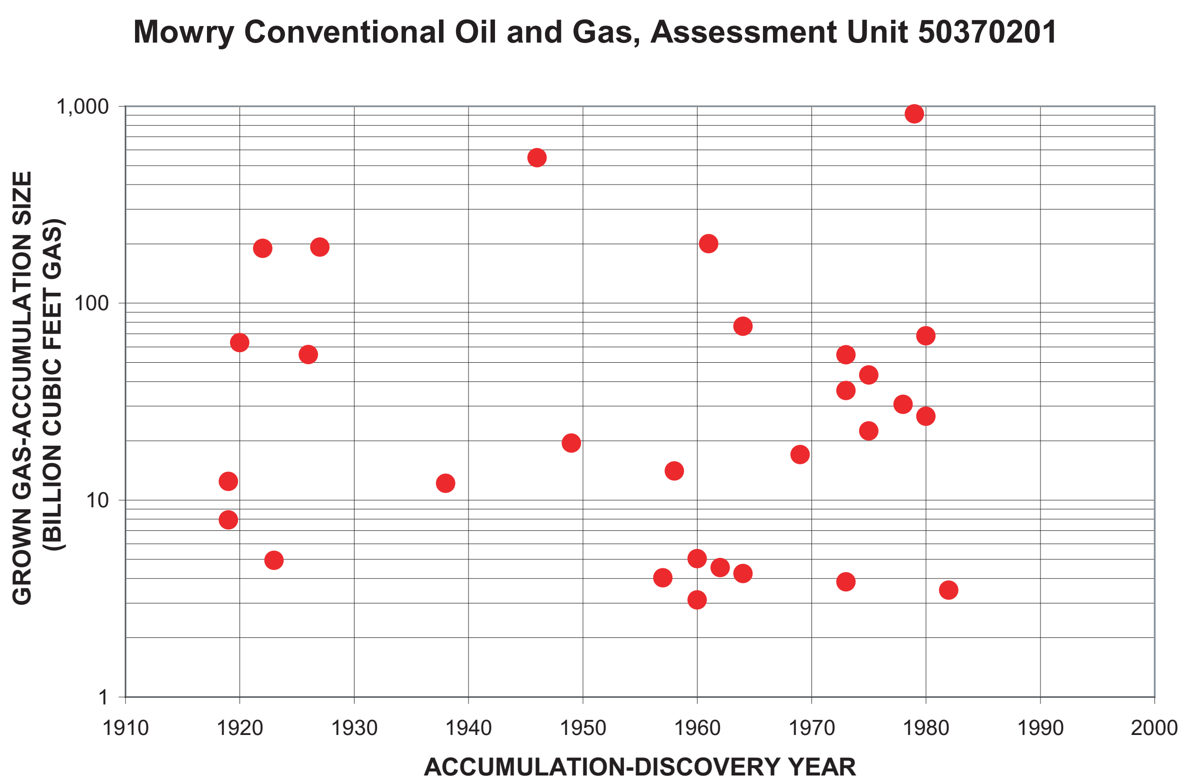


Figure 8. Plot showing size of grown gas accumulations (fields) relative to the discovery year for the Mowry Conventional Oil and Gas Assessment Unit 50370201. Data from NRG Associates (2001).

Mowry Composite Continuous Gas Assessment Unit (AU 50370261)

This assessment unit is defined as that part of the petroleum system where the following conditions favorable for continuous gas accumulations are met in wells (Spencer, 1987):

1. Overpressure exists.
2. The bottom hole temperature is greater than 200 degrees.
3. The vitrinite reflectance is greater than 0.8 percent.
4. Permeabilities are low.
5. No gas/water contacts have been reported.

These conditions are generally reached at depths of 8,000 to 12,000 ft in the province because of the interrelationship of heat flow, source rock maturity, and overpressuring due to gas generation in low-permeability rocks (see Law, 1984, his figs. 10, 12; Spencer, 1987, his fig. 5). The 10,000-ft depth contour at the top of the petroleum system approximates where the favorable conditions overlap for the Mowry Composite Total Petroleum System. The AU boundary is drawn to follow this contour except along where the AU boundary is defined by the footwall cutoff of the Hogsback-Prospect thrust, essentially the same boundary as the province and the TPS. The assessment unit includes a transition zone where reservoirs can be either gas charged or water saturated. Input data for this assessment unit are provided in Appendix B.

Characteristics of the Assessment Unit

Exploration of the province began in the early 1900's (IHS Energy Group, 2001); since then, 3,193 wells are interpreted to have tested the Mowry Composite TPS units for petroleum. Of these wells, 2,527 are listed as producers and 666 are interpreted to be dry holes for the TPS (fig. 9). Estimated ultimate recoveries (EUR) were calculated for about 550 of these producing wells completed between 1954 and 2000, and about 4 percent of these wells were determined to be below our minimum EUR of 0.02 BCFG. The 4 percent is extrapolated to all producing wells to give a value of 101 producing wells below the minimum EUR (fig. 9).

Production data used in this study included about 550 wells completed between 1954 and 2000 (fig. 10). An EUR distribution, truncated to include only wells producing above our minimum (0.02 BCF), was used to help predict the potential recoveries for future addition to reserves (figs. 10 and 11). For details of the methods used to calculate EURs see Cook (Chapter 23, this CD–ROM). The early third of the data had a median EUR of 0.5 BCF, the median being 50 percent of that sample. This EUR probably reflects limiting factors related to the technology of the day and the early geologic concepts that existed in the beginning stages of development. The second third, with a median EUR of 1.3 BCF, reflects success related to solving the technological and geological problems of the early third, while the late third, with a median value of 0.5 BCF suggests that the best wells may have already been drilled or that interference exists in drainage areas among wells (Ira Pasternack, Colorado School and Mines, written commun., 2004). Better technology and more subtle strategies may be needed to increase median EURs in the future.

Potential Additions to Reserves in the Next 30 Years

The estimated size of the assessment unit is 11,500,000 acres (fig. 3). Drainage area per cell of untested cells with potential for additions to reserves is estimated to be distributed within a range of 40 and 300 acres, with a median of 120 acres, and is based on current and anticipated well-spacing information for the assessment unit area. The area of the assessment unit that is already tested can be calculated by applying the median cell size of 120 acres to 3,193 tested cells drilled in the unit and equals about 4 percent. The untested area, about 96 percent of the 11.5 million acres, interpreted to have potential is based on the concept that these low permeability sandstones require enhanced natural fracturing or better than normal porosity in order to have completions above the minimum EUR.

A median value of about 9 percent of the untested assessment unit area is thought to have potential for additions to reserves in the next 30 years (Appendix B). The EUR distribution used for the untested area is based on historical values but is truncated to exclude wells below the 0.02 BCF minimum (fig. 11). The median estimated EUR of 0.7 BCF is based on the actual median value shown on the truncated EUR distribution (fig. 11), and the maximum EUR is estimated at 15 BCF based on the best historical well shown in the late third split (fig. 10).

Potential for adding to reserves in the next 30 years could come from:

1. Infill drilling around existing production;
2. Recompletions in the Frontier from producing holes in the Dakota or Morrison Formation;
3. Hypothetical accumulations in the Frontier, including:
   (a) Fractured areas around the flanks of the Rock Springs Uplift,
   (b) Top-truncated lowstand deltas in the Frontier east of the Rock Springs uplift, and
   (c) Possibly deeper targets in relatively thick reservoir units in the Frontier in the northeastern Great Divide Basin.

Infill drilling is expected to have a better success ratio than the historical ratio of 76 percent (fig. 9), stepout drilling

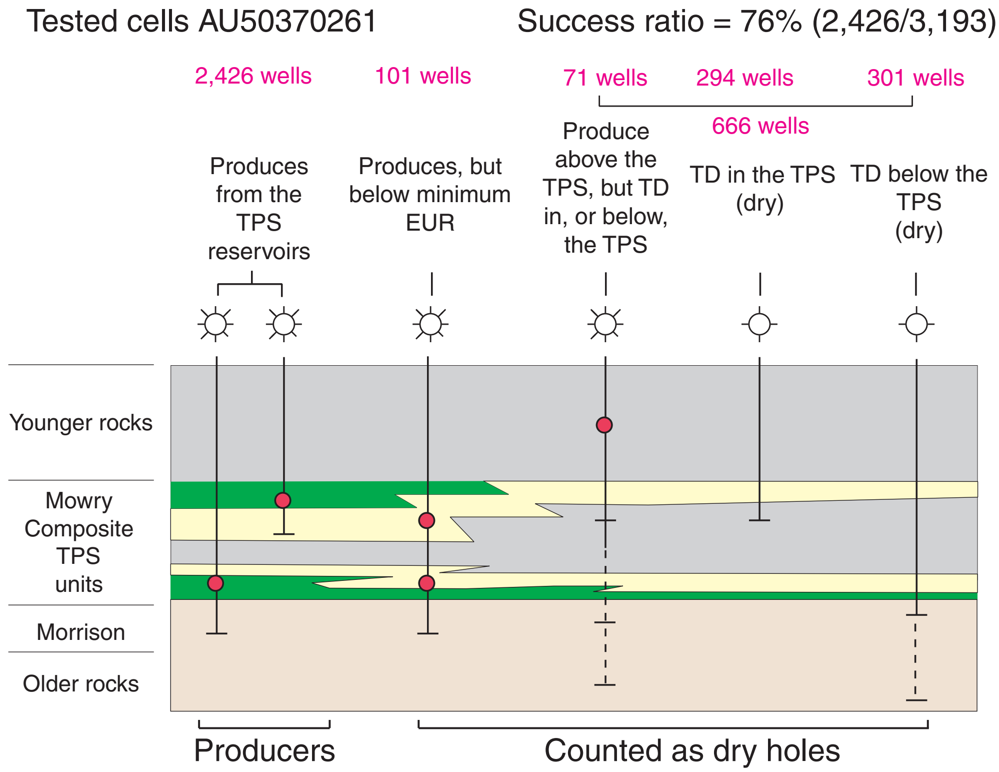


Figure 9. Graphic representation of producing and dry holes as determined for the Mowry Continuous Gas Assessment Unit 50370261. Producing wells plus dry holes equal tested cells (see Appendix B). Colors show general depositional environments (see fig. 2). Red dots denote perforated zone. Note: there are 101 wells that produced below our minimum cutoff (0.02 billion cubic feet of gas) and were not included in our final count of producers. [Abbreviations: EUR, estimated ultimate recovery; TPS, Total Petroleum System; TD, total depth]

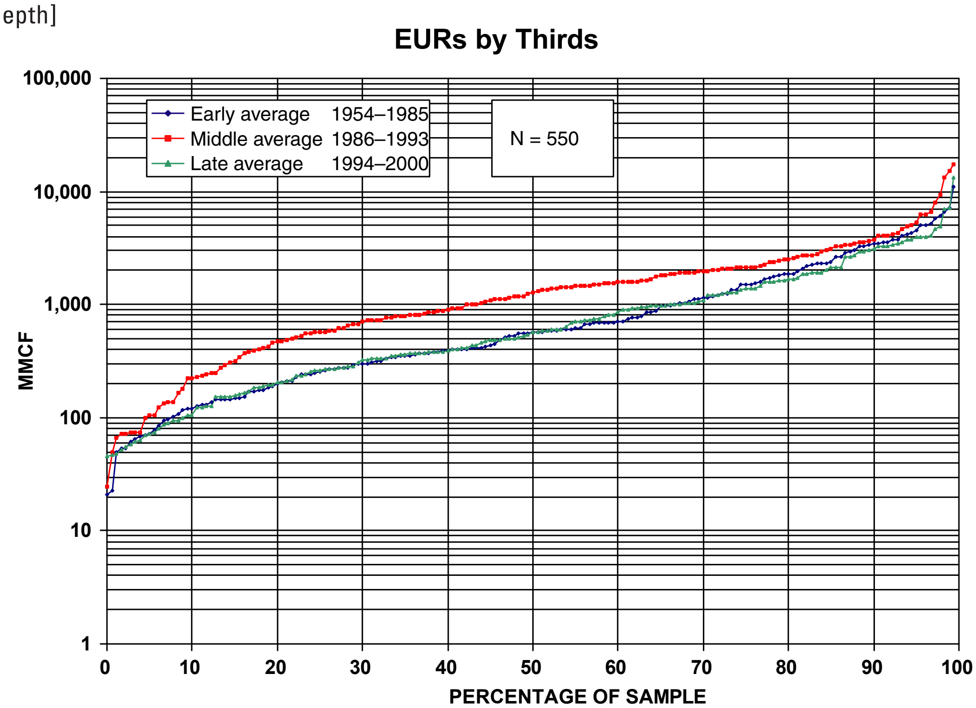


Figure 10. Truncated estimated ultimate recovery (EUR) thirds for wells producing from the Mowry Continuous Gas Assessment Unit. The curves are truncated to remove wells less than our minimum cutoff (< 0.02 billion cubic feet of gas). EURs were calculated from a sampling of 550 wells from IHS Energy Group (2001) completed between 1954 and 2000. Data provided by Troy Cook, U.S. Geological Survey. "Thirds" refers to the division into three parts, over time, of the wells drilled in a given area. In this usage, the wells are divided by time according to their completion date. [Abbreviations: MMCF, million cubic feet.]

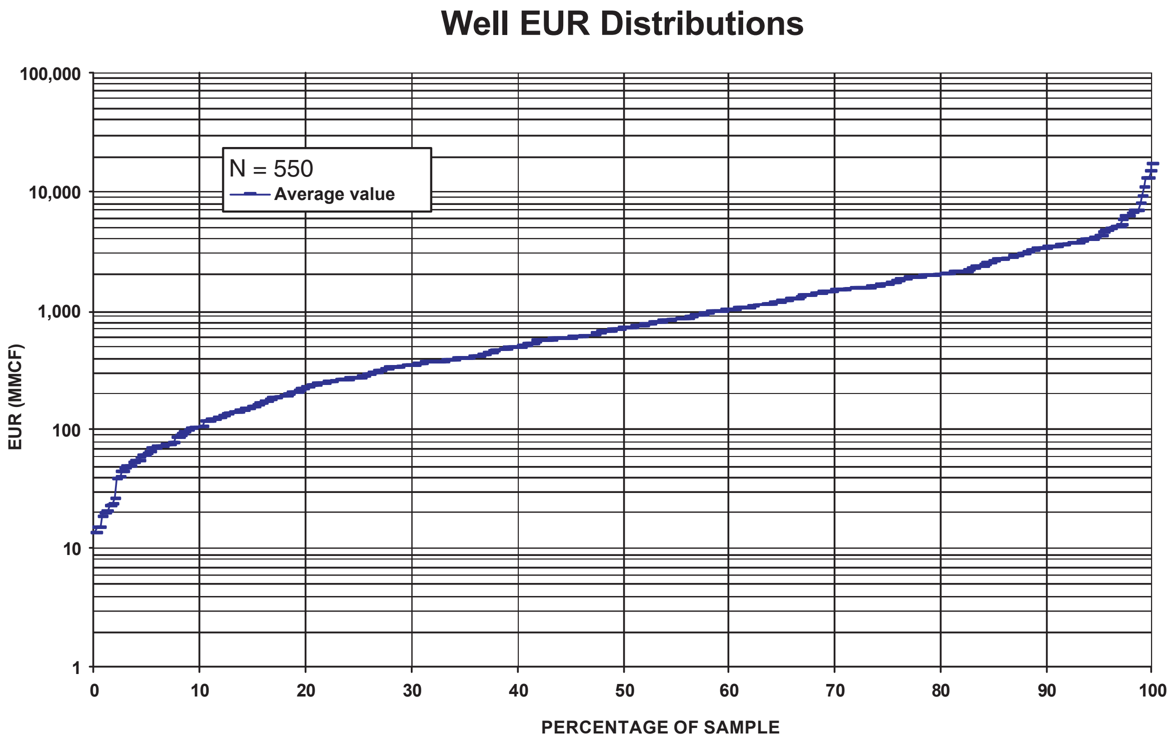


Figure 11. Truncated estimated ultimate recovery (EUR) distribution for wells in the Mowry Continuous Gas Assessment Unit completed between 1954 and 2000.

Table 1. Summary of assessment results for the Mowry Composite Total Petroleum System.

[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. 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**
Mowry Composite TPS													
Mowry Conventional Oil and Gas AU	***Oil***	1.70	5.70	14.80	6.60	2.70	9.40	25.90	11.20	0.30	1.30	3.70	1.60
	Gas					85.80	196.30	301.40	195.10	1.60	3.80	6.70	3.90
Total conventional resources		**1.70**	**5.70**	**14.80**	**6.60**	**88.50**	**205.70**	**327.30**	**206.30**	**1.90**	**5.10**	**10.40**	**5.50**
Mowry Continuous Gas AU	***Oil***	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Gas					6,745.90	8,461.90	10,614.40	8,542.80	110.90	165.80	247.90	170.90
Total continuous resources		**0.00**	**0.00**	**0.00**	**0.00**	**6,745.90**	**8,461.90**	**10,614.40**	**8,542.80**	**110.90**	**165.80**	**247.90**	**170.90**

is expected to have a similar success ratio (76 percent), and in undrilled areas, the ratio is expected to be less than the historical success ratio.

Assessment Results

The Mowry Conventional Oil and Gas Assessment Unit is estimated to contain a mean of 6.60 million barrels of oil, 11.20 billion cubic feet of associated gas, and 1.60 million barrels of associated natural gas liquids (table 1). Gas fields within the assessment unit are estimated at the mean to be 195.10 billion cubic feet of gas and 3.90 million barrels of natural gas liquids (table 1).

The Mowry Continuous Gas Assessment Unit has a mean estimate of 8,542.80 billion cubic feet of gas and 170.9 million barrels of natural gas liquids (table 1).

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Appendix A. Input data for the Mowry Conventional Oil and Gas Assessment Unit (AU 50370201). Seventh Approximation Data Form for Conventional Assessment Units (NOGA, version 5, 06-30-01). Complete form including allocations is shown 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:……..	M.A. Kirschbaum	Date:	8/21/2002
Region:………………………..	North America	Number:	5
Province:……………………….	Southwestern Wyoming	Number:	5037
Total Petroleum System:……	Mowry Composite	Number:	503702
Assessment Unit:……………	Mowry Conventional Oil and Gas	Number:	50370201
Based on Data as of:……….	NRG 2001 (data current through 1999), IHS Energy Group 2001, WGA Guidebooks		
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: 11 Gas: 29
Established (>13 accums.) X Frontier (1-13 accums.) ___ Hypothetical (no accums.) ___

Median size (grown) of discovered oil accumulation (mmbo):
1st 3rd 8 2nd 3rd 0.85 3rd 3rd ___
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd 37.2 2nd 3rd 9.5 3rd 3rd 30.6

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)

Oil Accumulations:…………………min. no. (>0)	1	median no.	3	max no.	7
Gas Accumulations:……………….min. no. (>0)	3	median no.	14	max no.	22

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

Oil in Oil Accumulations (mmbo):…..…min. size	0.5	median size	1.5	max. size	20
Gas in Gas Accumulations (bcfg):….….min. size	3	median size	12	max. size	80

Appendix A. Input data for the Mowry Conventional Oil and Gas Assessment Unit (AU 50370201). Seventh Approximation Data Form for Conventional Assessment Units (NOGA, version 5, 06-30-01). Complete form including allocations is shown in Klett and Le (Chapter 28, this CD–ROM).—Continued

Assessment Unit (name, no.)
Mowry Conventional Oil and Gas, Assessment Unit 50370201

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

Oil Accumulations:	minimum	median	maximum
Gas/oil ratio (cfg/bo)……………………...………	842	1,684	2,526
NGL/gas ratio (bngl/mmcfg)……………………...….	70	140	210

Gas Accumulations:	minimum	median	maximum
Liquids/gas ratio (bliq/mmcfg)………………..……..	10	20	30
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)…………………….………….	17.5	38	47
Sulfur content of oil (%)…………………………...…..	0.1	0.2	0.5
Drilling Depth (m) ……………...…………….……..	3,650	4,250	4,875
Depth (m) of water (if applicable)……………...…..			

Gas Accumulations:	minimum	median	maximum
Inert gas content (%)……………………….....…….	0.1	1	20
CO_2 content (%)……………………………….....….	0.2	0.6	3.2
Hydrogen-sulfide content (%)………………...…….	0	0	0
Drilling Depth (m)……………………………………	650	2,500	5,800
Depth (m) of water (if applicable)………………….			

Appendix B. Input data for the Mowry Continuous Gas Assessment Unit (AU 50370261). FORSPAN assessment model for continuous accumulations- Basic Input data form (Version 4, 10-05-00). Complete form including allocations is shown 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:…	M.A. Kirschbaum	Date:	8/20/2002
Region:……………………	North America	Number:	5
Province:…………………	Southwestern Wyoming	Number:	5037
Total Petroleum System:.	Mowry Composite	Number:	503702
Assessment Unit:……….	Mowry Continuous Gas	Number:	50370261
Based on Data as of:……	IHS Energy Group 2001 (data current through 2000)		
Notes from Assessor…..			

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo) Gas
What is the minimum total recovery per cell?… 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 3193
Number of tested cells with total recovery per cell ≥ minimum: …….. 2426
Established (>24 cells ≥ min.) X Frontier (1-24 cells) ____ Hypothetical (no cells) ____
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st 3rd discovered 0.5 2nd 3rd 1.3 3rd 3rd 0.5

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 11,229,000 median 11,458,000 maximum 12,010,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres): (values are inherently variable)
   calculated mean 130 minimum 40 median 120 maximum 300

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
   minimum 92 median 96 maximum 99

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 6 median 9 maximum 12

Appendix B. Input data for the Mowry Continuous Gas Assessment Unit (AU 50370261). FORSPAN assessment model for continuous accumulations- Basic Input data form (Version 4, 10-05-00). Complete form including allocations is shown in Klett and Le (Chapter 28, this CD–ROM).—Continued

Assessment Unit (name, no.)
Mowry Continuous Gas, Assessment Unit 50370261

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 0.7 maximum 15

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

Oil assessment unit:	minimum	median	maximum
Gas/oil ratio (cfg/bo)……			
NGL/gas ratio (bngl/mmcfg)……			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)……	10	20	30

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	0.75	11.00
CO_2 content (%)……	0.10	1.00	12.00
Hydrogen-sulfide content (%)……	0.00	0.00	0.00
Drilling depth (m)……	2,100	3,600	5,200
Depth (m) of water (if applicable)……			

Success ratios:	calculated mean	minimum	median	maximum
Future success ratio (%).....	76	61	76	91

Historic success ratio, tested cells (%). 76

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