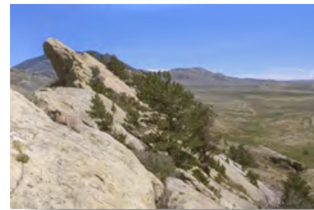
Chapter 6

Niobrara Total Petroleum System in the Southwestern Wyoming Province



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By Thomas M. Finn and Ronald C. Johnson

Chapter 6 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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Niobrara Total Petroleum System in the Southwestern Wyoming Province

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Abstract

The Niobrara Total Petroleum System (TPS) is a self-sourced system that produces oil and natural gas from fractured carbonate rock reservoirs in the Upper Cretaceous Niobrara Formation and equivalent rocks of the Southwestern Wyoming Province. The Niobrara TPS encompasses the area of eastern and southeastern Greater Green River Basin of southwestern Wyoming and northwestern Colorado. The Niobrara and equivalents were deposited during a major Late Cretaceous marine transgressive cycle that created conditions favorable for the deposition of fine-grained marine carbonate rocks and the preservation of organic matter. The Niobrara ranges in thickness from 900 to 1,800 feet and consists mainly of interbedded organic-rich shale, calcareous shale, and marl. The hydrocarbon source beds contain predominantly Type-II oil-prone organic matter with total organic carbon contents ranging from 0.85 to 2.75 weight percent. Thermal maturities range from less than 0.60 percent R_o (vitrinite reflectance) along the eastern and southern flanks of the basin to greater than 1.35 percent R_o in deeper parts of the basin. Because of the fine-grained nature of the Niobrara, petroleum production is dependant on fractures that develop in hard, brittle, carbonate-rich zones. These brittle calcareous reservoirs are overlain, underlain, and (or) interbedded with soft, ductile marine shales that inhibit migration and seal the hydrocarbons within the fractured reservoir zones. Burial-history reconstructions and petroleum generation models show that the Niobrara entered the oil window between 72 and 67 million years ago. Along the shallow flanks of the basin the Niobrara remains in the oil window. With continued subsidence and burial in the deeper portions of the basin, the Niobrara reached thermal maturities sufficient to crack oil to gas.

The Niobrara TPS is subdivided into two assessment units based on thermal maturity: a continuous oil assessment unit and a continuous gas assessment unit. The assessment units are characterized as “continuous-type” accumulations because they have the following characteristics: (1) no down-dip hydrocarbon/water contact, (2) little or no water production, (3) abnormally pressured, and (4) production independent of structural closure. The continuous oil assessment unit is an established assessment unit located in the updip parts of the eastern and southern flanks of the basin where thermal maturities are less than 1.35 percent R_o and generally are considered to be within the oil window. The continuous gas assessment unit is hypothetical and is located in the deeper portions of the basin where thermal maturities are greater than 1.35 percent R_o. The mean volume estimate of undiscovered oil resource for the Niobrara continuous oil assessment unit is 103.6 million barrels of oil. The hypothetical Niobrara continuous gas assessment unit was not quantitatively assessed because of a lack of production data and (or) a suitable analog.

Introduction

The Southwestern Wyoming Province (SWWP) (5037) is a large sedimentary and structural basin that formed during the Laramide orogeny (Late Cretaceous through Eocene). The SWWP covers approximately 23,000 mi^2 and occupies most of southwestern Wyoming, parts of northwestern Colorado, and a small area of northeastern Utah (fig. 1). The basin is structurally bounded on the west by the Wyoming thrust belt, on the north by the Wind River and Granite Mountains uplifts, on the east by the Rawlins, Sierra Madre, and Park uplifts, and on the south by the Uinta Mountains and Axial Basin uplift. The Niobrara Total Petroleum System (TPS) (503703) produces primarily oil from fractured, calcareous-rich shales, shaley limestones, and marls from the Upper Cretaceous Niobrara Formation or equivalent rocks, in the eastern portions of the Greater Green River Basin (GRRB).

Acknowledgments

The authors thank R.M. Pollastro and C.J. Schenk of the U.S. Geological Survey (USGS) National Oil and Gas Assessment team for discussions regarding the assessment of the Niobrara Total Petroleum System. We would also like to thank Troy Cook (USGS) for interpretation of production data, and providing graphs of EURs; P.H. Nelson and Joyce Kibler (USGS) for providing drill-stem test and pressure data; L.N. Roberts (USGS) for providing key maps, and burial history

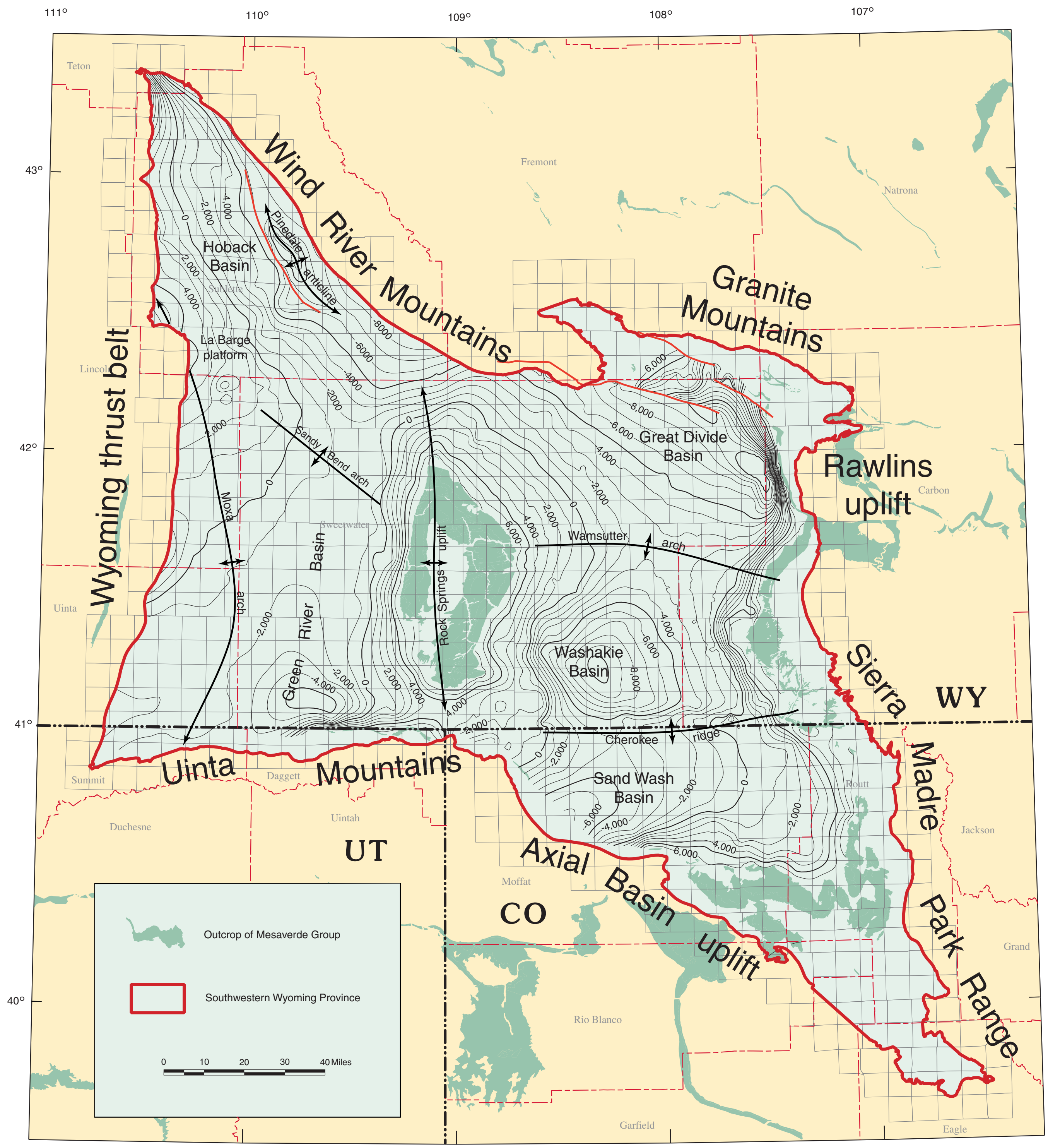

Figure 1. Index map of southwestern Wyoming, northeastern Utah, and northwestern Colorado showing the location of the Southwestern Wyoming Province, structural configuration, intrabasin uplifts, and subbasins. Structure contours drawn on top of the Mesaverde Group. Contour interval = 1,000 feet.

and petroleum-generation models; and P.G. Lillis and M.D. Lewan (USGS) for providing geochemical data and numerous discussions regarding organic geochemistry and source rocks. This manuscript was reviewed by R.M. Pollastro and M.J. Pawlewicz of the USGS, and their suggestions and comments are greatly appreciated.

Structural and Tectonic Setting

The western margin of the SWWP is formed by the Wyoming thrust belt (fig. 1), an easterly bulging salient of the Sevier orogenic belt that began to form in latest Jurassic or earliest Cretaceous time and ended in the Eocene (Armstrong and Oriel, 1965). The western margin is an area that is characterized by imbricate, gently west-dipping, east-directed decollement-style (thin-skinned) thrust faults that involve only sedimentary rocks, and north-trending folds (Royse and others, 1975). A broad, asymmetric foreland basin developed east of the Sevier orogenic belt in response to tectonic and sediment loading (Jordan, 1981), and during much of the Cretaceous Period the foreland basin was partially to completely flooded by the Western Interior Seaway (fig. 2). The seaway formed in response to the presence of the subsiding foreland basin and periodic eustatic rise in sea level. By the close of the Cretaceous Period (Maastrichtian) the western shoreline of the seaway retreated eastward as the foreland basin gradually filled in with sediments derived from the eroding uplifts of the Sevier orogenic belt (fig. 2). The end of the Cretaceous also marks the onset of the Laramide orogeny, a period of crustal instability and compressional tectonics in the foreland basin that continued into the Eocene. During the Laramide orogeny, the foreland basin was fragmented into numerous smaller basins that were each flanked by rising basement-cored uplifts. The smaller basins, such as the Greater Green River Basin, subsided rapidly and were depocenters for the accumulation of thick lacustrine and continental sediments.

Present-day structure of the SWWP is largely a result of Laramide compressional deformation that is characterized by basement-involved thrust faults (thick-skinned), reverse faults, wrench faults, and strongly folded and faulted anticlines and synclines. The north, south, and eastern margins of the basin are formed by Precambrian basement-cored uplifts that in many places have overridden the sedimentary basin section along high-angle basement-involved (thick-skinned) thrust faults (Ryder, 1988). Several major intrabasin uplifts are present in the SWWP and include the Moxa arch, La Barge platform, Sandy Bend arch, Rock Springs uplift, Wamsutter arch, and Cherokee ridge (fig. 1). Several of these intrabasin uplifts subdivide the SWWP into smaller structural and topographic subbasins. The most prominent of these uplifts is the north-south-trending Rock Springs uplift, a doubly plunging asymmetric anticline that divides the SWWP into nearly equal halves. West of the Rock Springs uplift, the northwest-southeast-trending Sandy Bend arch extends from the La Barge platform to the west flank of the Rock Springs uplift and separates the Green River Basin (sometimes referred to as the Bridger Basin) on the south from the Hoback Basin to the north. East of the Rock Springs uplift, the east-west-trending Wamsutter arch extends from the eastern flank of the Rock Springs uplift to south of the Rawlins uplift and separates the Great Divide Basin in the northeast corner of the SWWP from the Washakie Basin. The Cherokee ridge roughly parallels the Colorado-Wyoming State line and separates the Washakie Basin on the north from the Sand Wash Basin on the south (fig. 1).

Depositional Setting

During Late Cretaceous time, a broad epicontinental seaway, the Western Interior Seaway, extended from the Arctic Ocean to the Gulf of Mexico. The seaway (fig. 2) inundated an asymmetric foreland basin that was bordered on the west by the tectonically active highlands of the Sevier orogenic belt that supplied sediment to eastward-flowing streams. The eastern shore was on the stable cratonic platform that supplied little sediment (Molenaar and Rice, 1988; Williams and Stelck, 1975). During much of Late Cretaceous time, the sea advanced and retreated across the western part of the foreland basin, resulting in a complex pattern of intertonguing marine and nonmarine deposits. The nonmarine deposits are represented by eastward-thinning clastic wedges of sandstone, siltstone, shale, and coal. The marine deposits are represented by westward-thinning tongues of marine shale and siltstone (fig. 3). In the eastern and central sediment-starved parts of the seaway, clastic input was minimal, creating conditions favorable for carbonate deposition. In the eastern and southeastern portions of the SWWP, carbonate-rich sediments are represented by the Niobrara Formation and equivalent rocks in the lower parts of the Mancos and Steele Shales.

Niobrara Formation

The Niobrara Formation and laterally equivalent rocks were deposited during a period of high eustatic sea level and crustal subsidence in the Western Interior Seaway, resulting in a major marine transgression and conditions favorable for carbonate deposition. In the eastern part of the seaway where clastic input was minimal, chalks and limestone are the principal lithologies of the Niobrara in the Denver Basin of eastern Colorado (Pollastro and Scholle, 1986). In the SWWP, the Niobrara and equivalent rocks reflect a gradual westward decrease in chalk and other carbonate components and an increase in siliciclastic sediments because of its closer proximity to the detrital source, the thrust belt to the west. In the SWWP, the Niobrara Formation and equivalent rocks consist of interbedded organic-rich shale, calcareous shale, and marl, with minor amounts of sandstone, siltstone, lime-

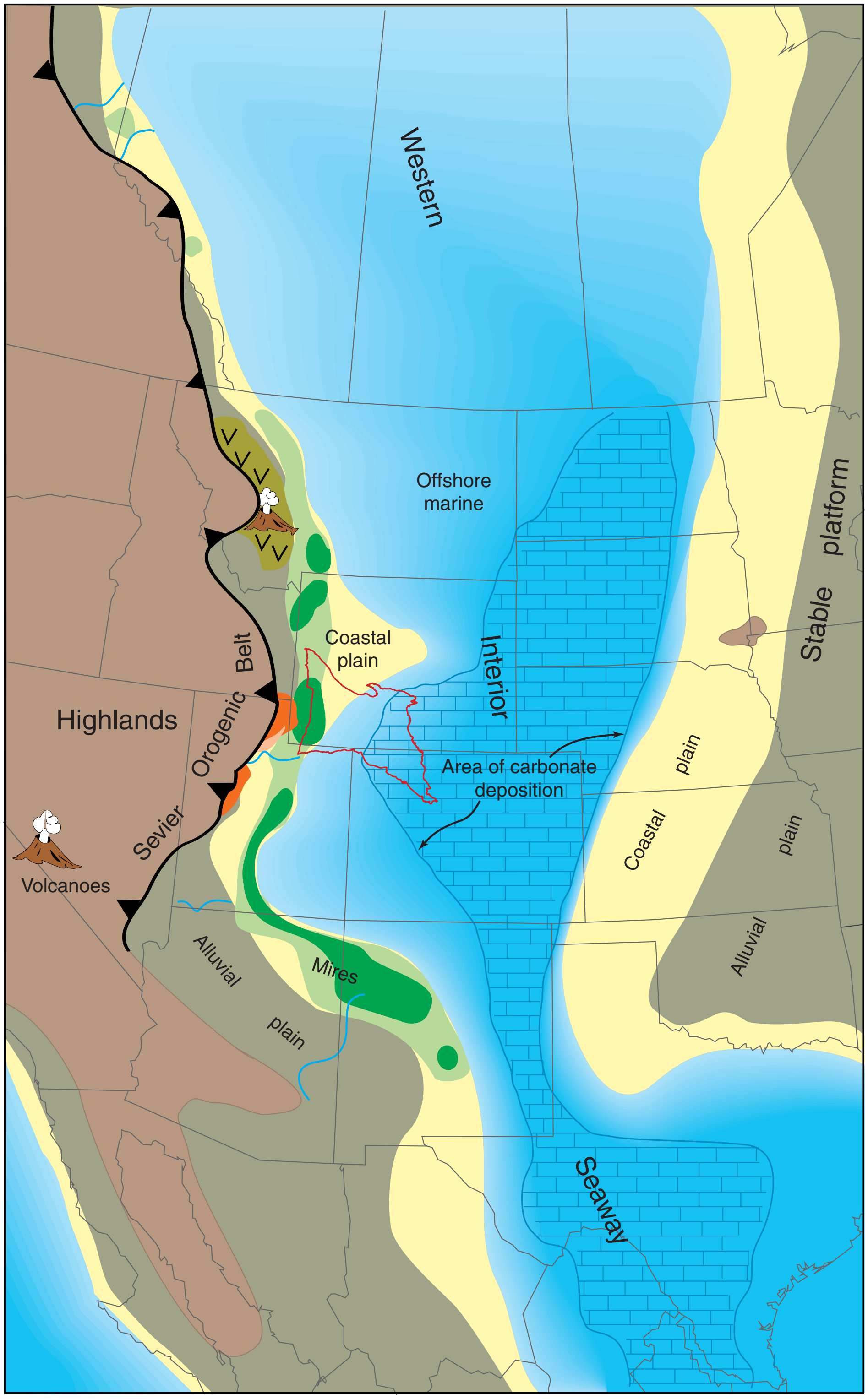

Figure 2. Paleogeographic reconstruction of the Western Interior Seaway during Coniacian-Santonian time. Modified from Roberts and Kirschbaum, 1995. Southwestern Wyoming Province is outlined in red.

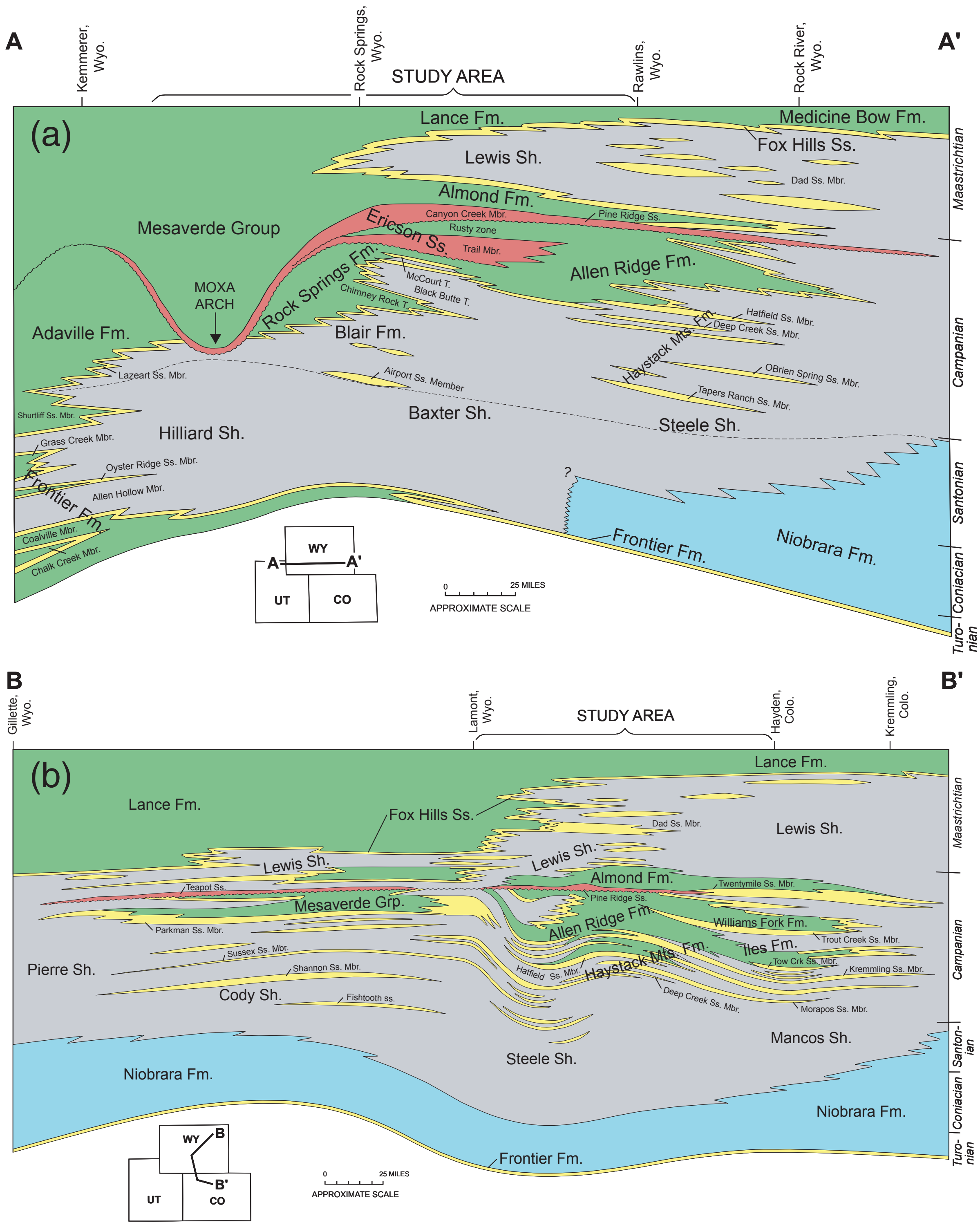

Figure 3a,b. Generalized regional stratigraphic cross sections of restored Upper Cretaceous rocks. A–A′ extends east-west across southern Wyoming, and B–B′ extends north-south from northern Wyoming to northwestern Colorado. Cross sections show the complex intertonguing relationship between marine and nonmarine deposits. Rocks of fluvial origin are shown in red; coastal plain, green; marine-shoreline, shelf, and slope sandstones and siltstones, yellow; marine shale, gray; calcareous-rich marine deposits are shown in blue. Modified from Roehler, 1990.

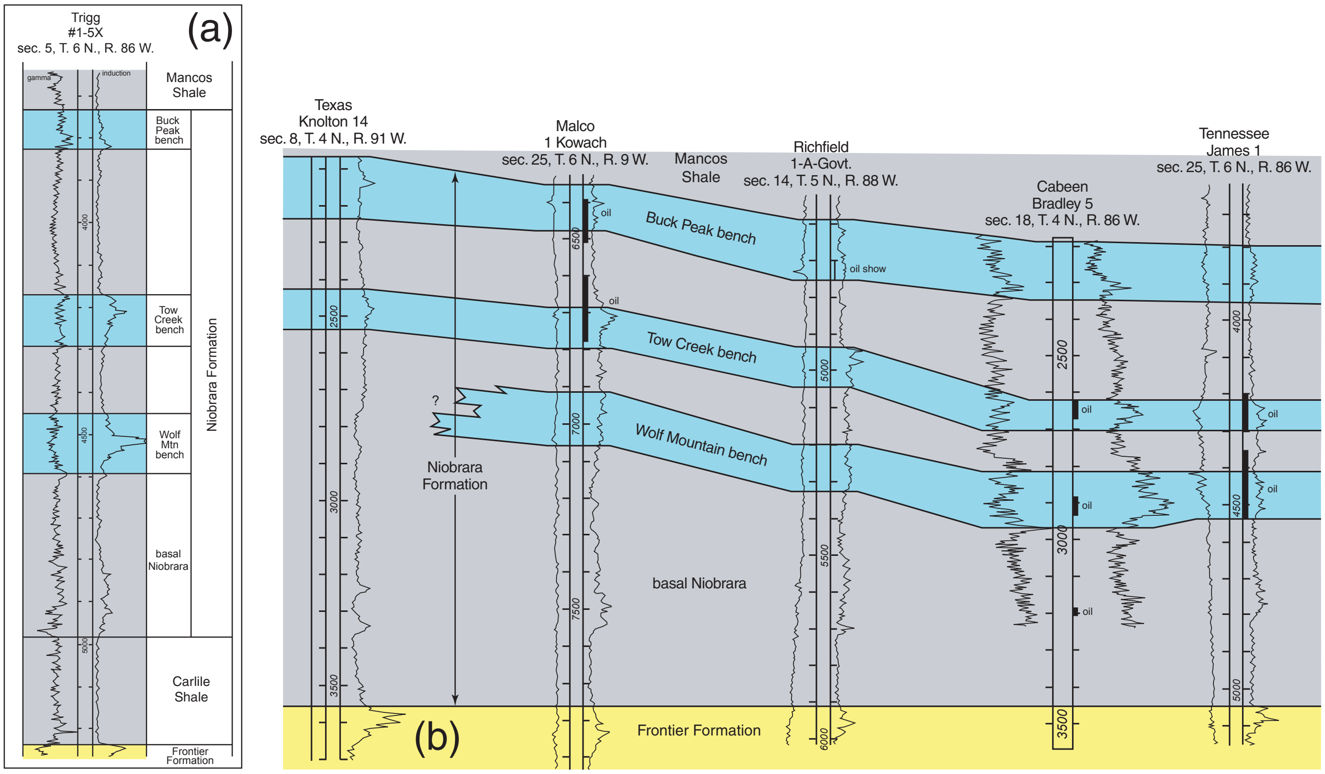

Figure 4. Type log (a) and subsurface cross section (b) of the Niobrara Formation in northwestern Colorado. Marine sandstones are shown in yellow, clay-rich marine shale in gray. Calcareous-rich zones that are more prone to fracturing are highlighted in light blue. Type log modified from Vincelette and Foster, 1992. Subsurface cross section modified from Haskett, 1959. Heavy vertical black bars indicate oil-producing zones. Location of type log and line of section are shown in figure 7.

stone, and chalk (Vincelette and Foster, 1992; Longman and others, 1998). A 200- to 400-ft-thick zone directly overlying the Frontier Formation has been identified by Vincelette and Foster (1992) as the Carlile Shale (fig. 4a). This zone, identified on well logs by a lower resistivity response than adjacent units, consists of clay-rich, noncalcareous marine shale and is included with the Niobrara in this study. This conforms with usage by numerous authors including Haskett (1959) (fig. 4b), Kucera (1959), and Hale (1961). To the west and north, typical Niobrara facies grades into noncalcareous marine shale, sandstone, and siltstone of the Baxter Shale (fig. 3a; also Finn and Johnson, Chapter 14, this CD–ROM, their pl. 1). The western limit of this facies change occurs in the deeper, sparsely drilled portions of the Sand Wash, Washakie, and Great Divide Basins; however, the limits of the Niobrara calcareous facies of the Niobrara are not well mapped.

The Niobrara is underlain by the Frontier Formation and overlain by a thick sequence of marine shale. In the Sand Wash Basin in Colorado, the thick overlying marine section is named the Mancos Shale; in the Washakie and Great Divide Basins of Wyoming it is named the Steele Shale (fig. 5). The basal contact of the Niobrara is well defined and coincides with the uppermost sandstone of the underlying Frontier Formation. The upper contact is transitional with the overlying Mancos or Steele Shales and is not well defined in the subsurface but is identified by a distinctive high-resisitivity kick on electric well logs (fig. 4; also Finn and Johnson, Chapter 14, this CD–ROM, their pl. 1). Regional studies by Longman and others (1998) show that the thickness of the Niobrara and equivalent rocks varies from less than 100 ft in South Dakota to more than 1,800 ft in west-central Wyoming, with a range of thickness in the eastern portions of the Southwestern Wyoming Province of 900 to 1,800 ft (fig. 6). This prominent westward thickening of the Niobrara is due to the large influx of siliciclastic sediments derived from actively eroding highlands of the thrust belt to the west.

The age of the Niobrara is considered to be Coniacian to Santonian (Hale, 1961), and Bader and others (1983) show that the upper part of the Niobrara corresponds to the ammonite zone of *Desmoscaphites bassleri*. This species, which is late Santonian, also occurs in a marker bed several hundred feet below the top of the Airport Sandstone Member of the Baxter Shale in exposures on the Rock Springs uplift (Smith, 1965). A similar age is reported by Smith (1961) for the basal part of the Lazeart Sandstone Member of the Adaville Formation in the thrust belt near Kemmerer, Wyoming.

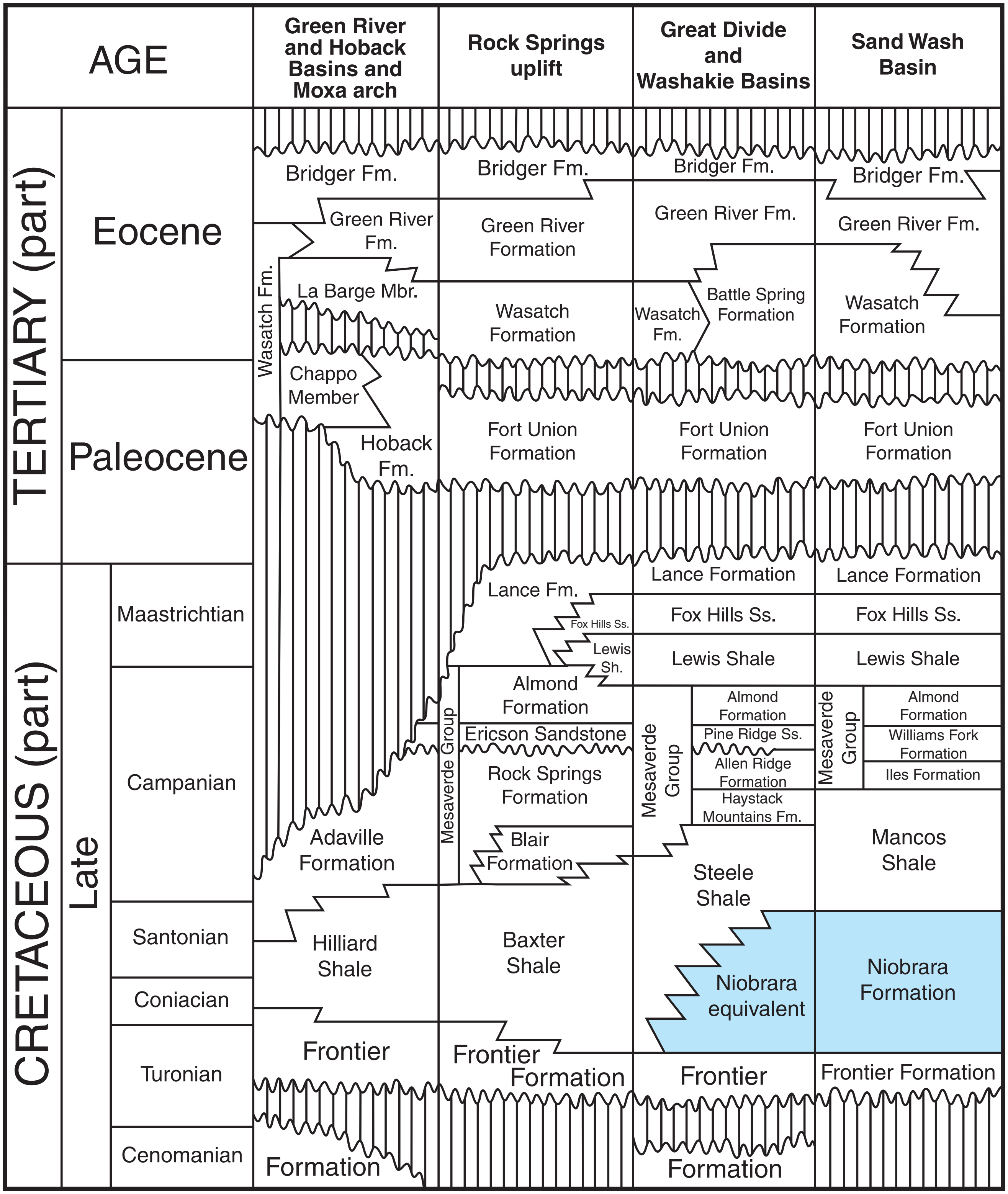

Figure 5. Generalized correlation chart of Cretaceous and lower Tertiary rocks in the Southwestern Wyoming Province. The stratigraphic interval contained in the Niobrara Total Petroleum System is highlighted in light blue. Modified from Ryder, 1988.

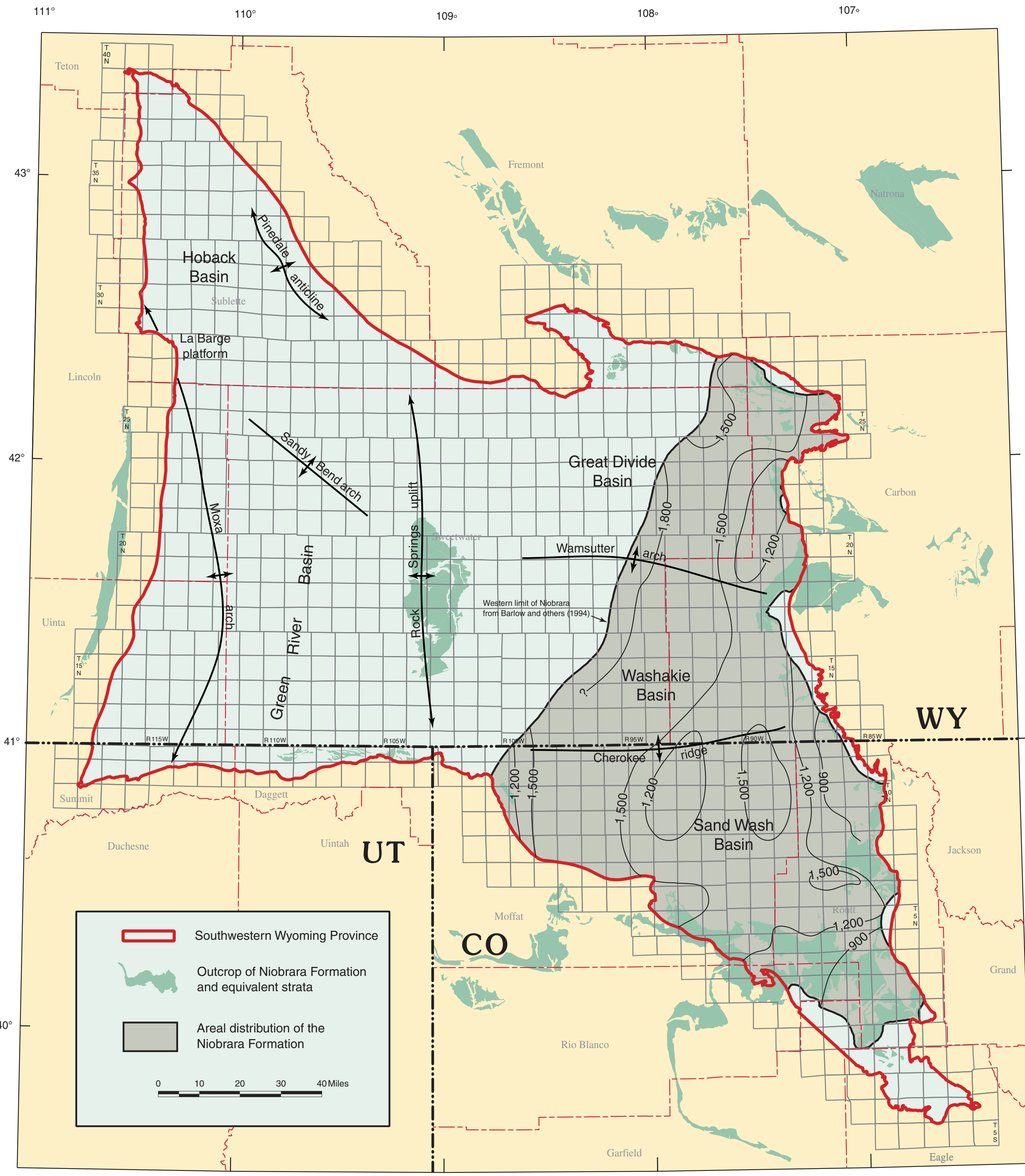

Figure 6. Isopach map showing the distribution and thickness of the Niobrara Formation in the Southwestern Wyoming province. Thickness in feet. Contour interval = 300 feet. Modified from Longman and others, 1998.

Niobrara Total Petroleum System (503703)

The Niobrara Total Petroleum System (TPS) (503703) produces self-sourced oil and natural gas from low-permeability, fractured, carbonate-rich rocks in the Upper Cretaceous Niobrara Formation and from its stratigraphic equivalents in the lower parts of the Mancos and Steele Shales. The Niobrara TPS encompasses the eastern one-third of the SWWP and covers approximately 8,400 mi^2 of the Sand Wash, Washakie, and Great Divide Basins (fig. 7). The eastern and southeastern boundaries of the TPS are defined by the base of the outcrop of the Niobrara or equivalent rocks at the base of Mancos or Steele Shales. The southern boundary is the Axial Basin uplift (fig. 1). The western boundary is poorly defined because few wells have penetrated the Niobrara in the deeper portions of the Sand Wash, Washakie, and Great Divide Basins. The western boundary is defined here to coincide with subsurface mapping presented by Barlow and others (1994). Oil production in this area appears to be restricted to the Niobrara, and geochemical data indicate no other reservoirs contain Niobrara sourced oil (P.G. Lillis, oral commun., 2002,). Thus, stratigraphically, the Niobrara TPS is constrained to the Niobrara Formation and equivalent rocks (fig. 5).

Source Rocks

Regional studies by Landon and others (2001) and Meissner and others (1984) indicate that organic matter in the Niobrara Formation is Type-II, oil-prone kerogen. The sediments were deposited during a major marine trangressive cycle known as the Niobrara cyclothem (Kauffman, 1977) during which highstand conditions persisted. This resulted in basin deepening that produced anoxic conditions favorable to the preservation of organic matter. According to Landon and others (2001), the richest source rocks are in the Denver Basin with total organic carbon (TOC) contents ranging up to about 8 weight percent in areas that were sediment-starved along the foreland basin. Westward into south-central Wyoming the TOC content decreases to 2.14 weight percent (Landon and others, 2001) because influx of siliciclastic sediments from the western area diluted the organic matter. Vincelette and Foster (1992) report that up to 700 ft of the Niobrara has source-rock potential in northwestern Colorado.

Rock-Eval data for 28 Niobrara samples (U.S. Geological Survey Organic Geochemistry Database) from well cuttings from northwestern Colorado and south-central Wyoming were plotted on a modified van Krevelen diagram (Espitalie and others, 1977), a graph of S_2 vs. %TOC (Langford and Blanc-Valleron, 1990), and a hydrogen index vs. Tmax diagram (Bordenave and others, 1993) (fig. 8). These plots indicate that the majority of the samples are Type-II, oil-prone kerogen with some mixing from Type-III, gas-prone kerogen. The Type- III kerogen was most likely derived from terrestrial sources along the western shoreline, and (or) from cavings from the overlying Mancos Shale. TOC values for the same 28 Niobrara samples ranged from 0.85 to 2.75 weight percent (fig. 8a) with an average of 1.85 weight percent. For samples with Tmax values less than 435 (fig. 8a), TOC content increased and ranged from 1.1 to 2.75 weight percent with an average of 2.06 weight percent.

Reservoir Rocks

The lithology of the Niobrara Formation and equivalent strata in the eastern part of the province is composed of interbedded calcareous shale, shaley limestone, and marls. The fine-grained nature of these lithologies results in little matrix porosity or permeability, therefore production is dependent on fractures. Vincelette and Foster (1992) have identified several discrete zones of calcareous shale, shaley limestone, or marl informally referred to as the Wolf Mountain, Tow Creek, and Buck Peak benches that account for the majority of Niobrara production (fig. 4). These benches have greater carbonate content than adjacent, more shaley beds and form hard, brittle zones that promote fracturing and produce good reservoirs. Reservoir zones typically range from 50 to 200 ft in thickness, but in some wells may be as much as about 400 ft thick.

Detailed fracture studies from surface and subsurface rocks in northwest Colorado show that the fractures in the Niobrara are mineralized and contain either calcite, quartz, or gypsum (Vincelette and Foster, 1992; Saterdal, 1955). These vein-filling minerals may partially line or completely plug fracture systems and reduce permeability. Vincelette and Foster (1992) found that many fractures associated with Laramide structures were completely filled by calcite, which resulted in poor reservoir performance. In contrast, the best production is from reservoirs with fractures associated with Neogene-age extensional features where calcite cements line, rather than plug, fractures within productive reservoirs (Vincelette and Foster, 1992). Vincelette and Foster also found that many of the productive fractures associated with Laramide structures that were initially plugged with calcite vein material were reopened by later Neogene extension, particularly in areas where preexisting fractures were oriented with structures formed by post-Laramide extension. In these cases, fractures were reopened along preexisting zones of weakness and lined, but not completely filled, by calcite.

Seal Rocks

A thick section (up to several thousand feet) of soft, noncalcareous Mancos or Steele Shale provides a good quality regional seal over the Niobrara Formation within the TPS (Finn and Johnson, Chapter 14, this CD–ROM, their plate 1). In addition, hard, brittle reservoir zones within the Niobrara

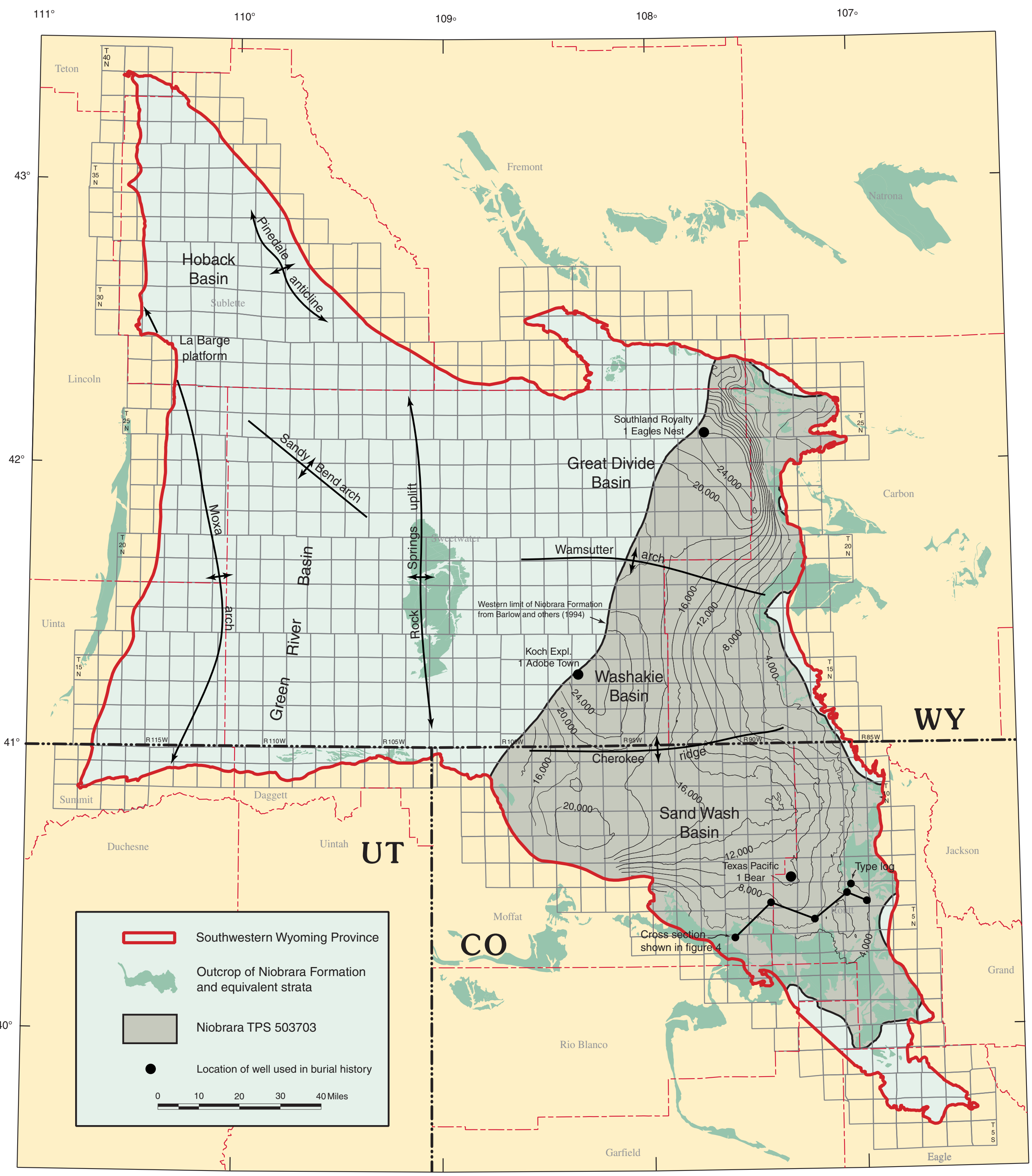

Figure 7. Map of the Southwestern Wyoming Province showing the extent of the Niobrara Total Petroleum System, major structural elements, location of type log and cross section, and location of wells used in burial reconstructions. Contours represent the approximate depth in feet to the base of the Niobrara Formation (modified from Kirschbaum and Roberts, Chapter 5, this CD–ROM). Contour interval = 2,000 feet.

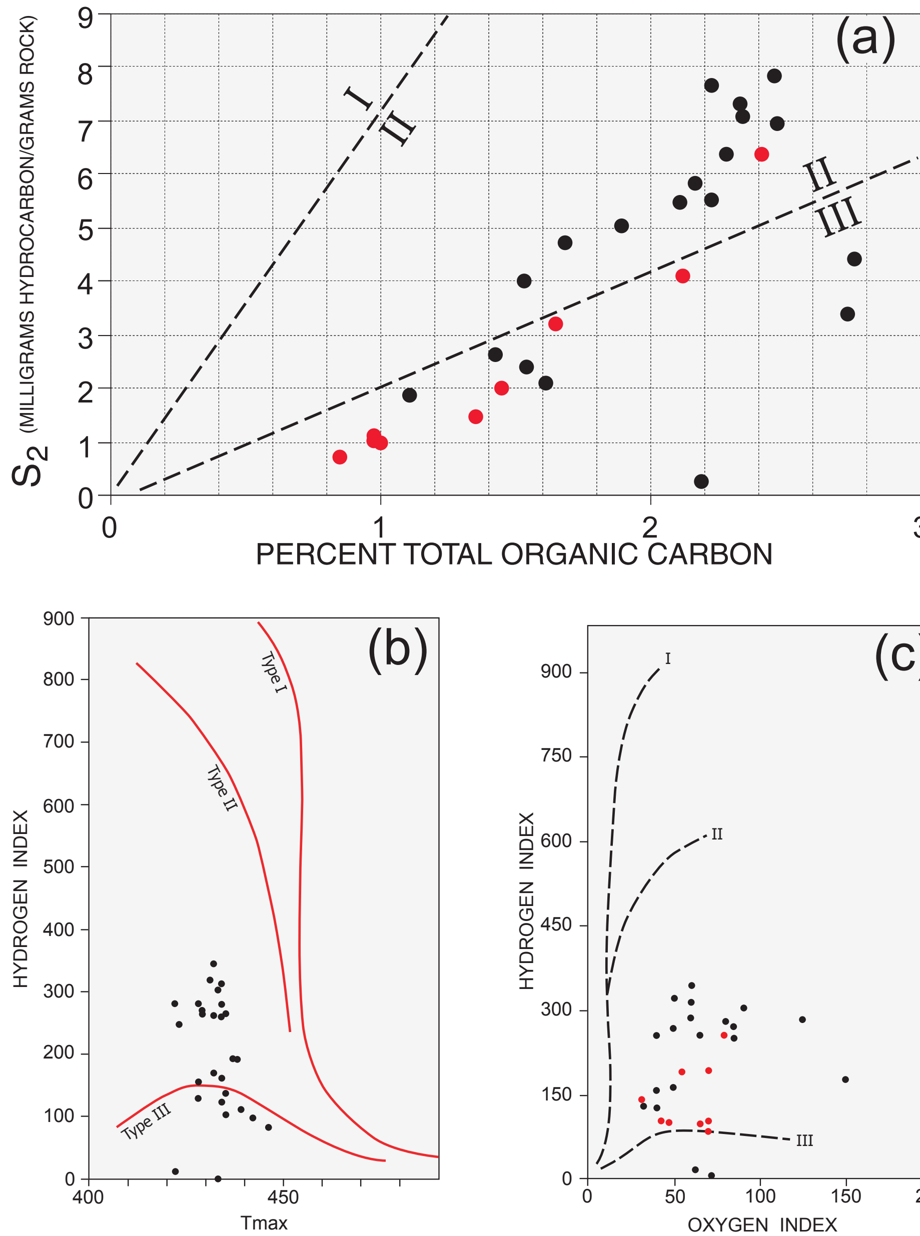

Figure 8. Plots of data from Rock-Eval analysis of kerogen of 28 Niobrara Formation samples, USGS Organic Geochemistry Database. The samples are from well cuttings from northwestern Colorado and south-central Wyoming (the samples from northwestern Colorado are from the Sand Wash Basin and the northern part of the Piceance Basin), (a) S_2 vs. total organic carbon, (b) hydrogen index vs. Tmax, and (c) modified van Krevelen diagram. Majority of samples indicate a Type-II oil-prone kerogen with some Type-III. Black dots represent samples with a Tmax < 435, red dots represent samples with a Tmax ≥ 435.

are overlain, underlain, and (or) interbedded with relatively ductile, clay-rich marine shales that are lower in carbonate content than the adjacent reservoirs (fig. 5). These soft, plastic zones are not as prone to fracturing and tend to seal the hydrocarbons within the fractured reservoirs (Mallory, 1977; Pollastro, 1992).

Traps

Most Niobrara production is from fractured reservoirs associated with Laramide-age folding (fig. 9) and, according to Vincelette and Foster (1992), fracture production occurs along the crestal parts of anticlines as well as down both the steep and gentle flanks where production is independent of structural closure. These fractures formed in response to folding and faulting of brittle reservoir rocks during Laramide compressional tectonics. Additional production comes from fractures or fracture swarms that are associated with faults and fault systems formed during post-Laramide Neogene extension (Vincelette and Foster, 1992); the best producing wells intersect or are in close proximity to normal faults. According to Hansen (1986) post-Laramide extension began early in the Miocene and continued into the Quaternary at a diminishing rate.

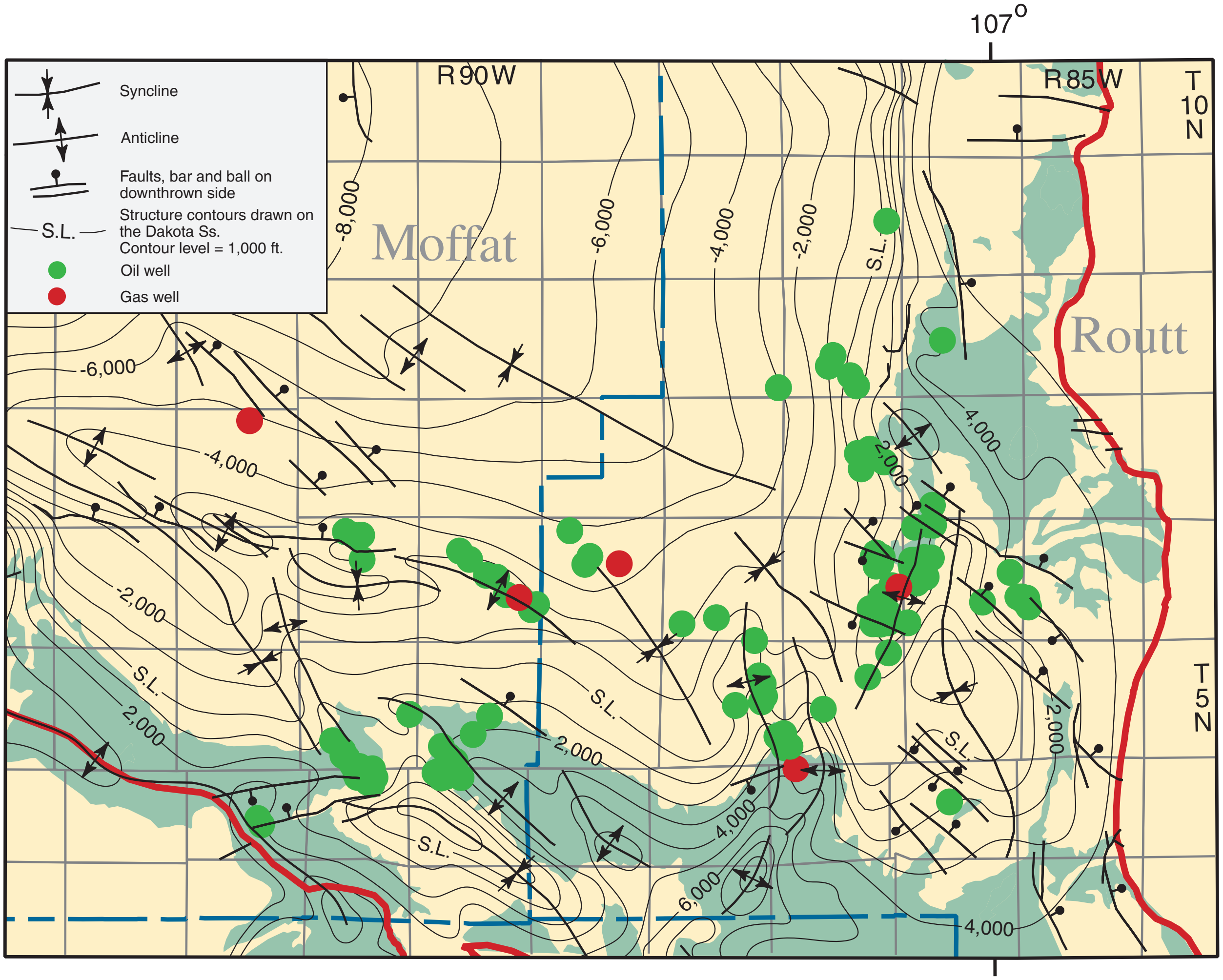

Figure 9. Structure contour map on the Dakota Sandstone in the southern part of the Sand Wash Basin showing the relationship of Niobrara Formation production to fold axes and faults. Heavy red line is the Southwestern Wyoming Province boundary. Sources of structural data are Tweto (1976, 1979) and Barlow and Haun, Inc. (1997) Abbreviation S.L., sea level.

Thermal Maturity

Thermal maturity mapping of the Niobrara from vitrinite reflectance (R_o) data shows a general increase in maturity westward into deeper parts of the basin. R_o values range from less than 0.60 percent along the flanks of the basin, to greater than 1.35 percent in the deeper portions of the Sand Wash, Washakie, and Great Divide Basins (fig. 10). Thermal maturity generally reflects the structural configuration of the basin and indicates that thermal maturation trends are related to the structural development of the basin. The 0.60 percent R_o contour is the lower limit of oil generation from Type-II organic matter and geographically defines the pod of mature source rock. Areas that are less than 0.60 percent R_o are considered thermally immature, and the generation of oil or thermogenic gas is not expected. The "oil window" for Type-II organic matter is commonly considered to be in the range of 0.60 to 1.35 percent R_o (Hunt, 1996). Thus, Niobrara oil accumulations are predicted for those areas where the R_o is between 0.60 and 1.35 percent. The level of thermal maturity needed to initiate the thermal cracking of oil to gas is not well known but is generally considered to be greater than 1.35 percent R_o (Law, 2002); therefore, Niobrara gas accumulations are predicted for those areas where the R_o is greater than 1.35 percent. Direct measurements of thermal maturity were unavailable for Niobrara samples; therefore, R_o data were collected from the overlying coal-bearing Mesaverde Group and Lance and Fort Union Formations (Law, 1984; Pawlewicz and others, 1986; Merewether and others, 1987; and Pawlewicz and Finn, 2002). These data were plotted on a R_o versus depth graph and a visual best-fit line was drawn through the points and extrapolated to the Niobrara horizon (fig. 10).

Hydrocarbon Generation

Burial-history curves using PetroMod1D Express (version 1.1) (see Roberts and others, Chapter 3, this CD–ROM, for detailed discussion of petroleum generation models, and parameters used to generate burial and thermal histories)

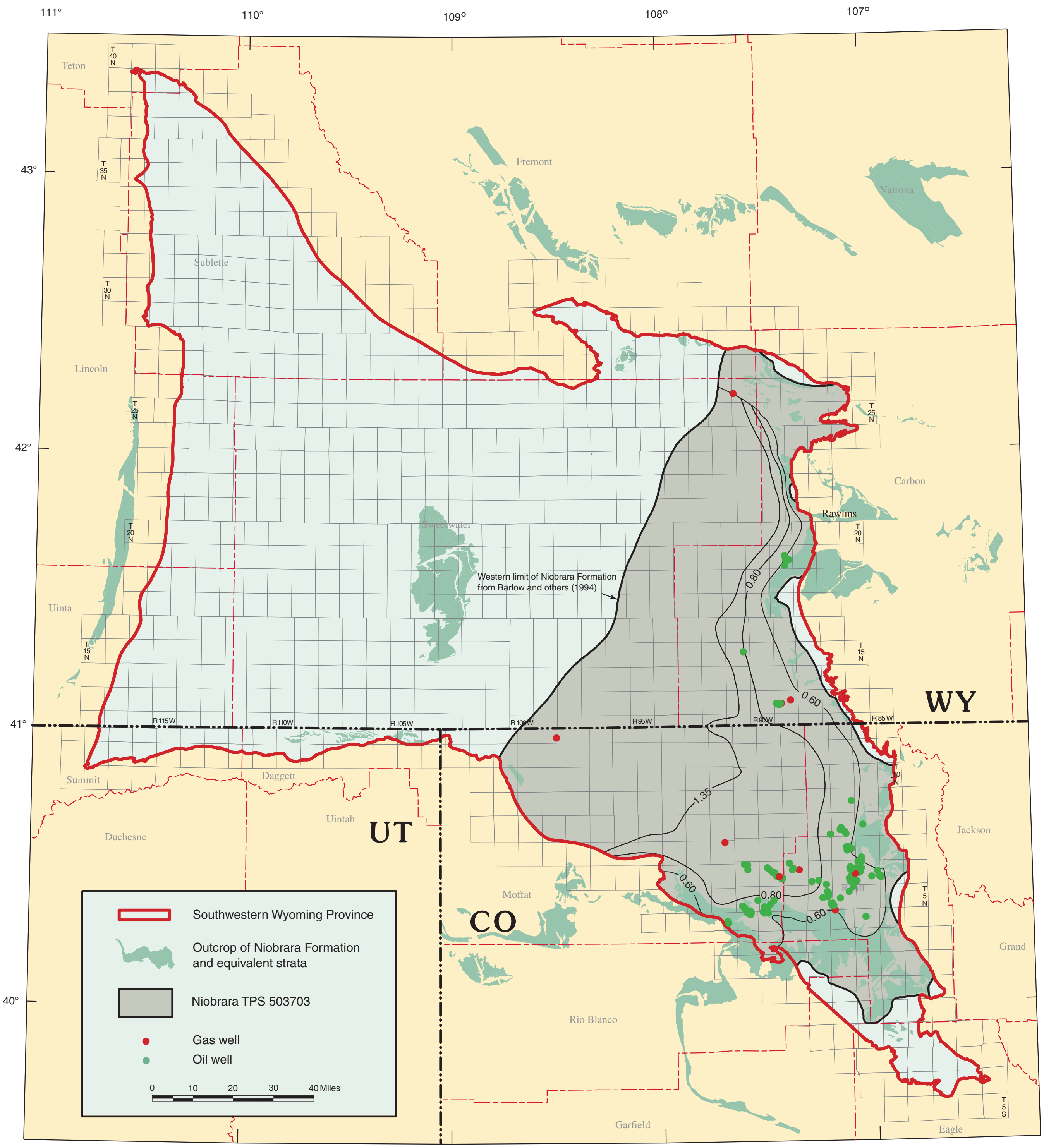

Figure 10. Eastern part of the Southwestern Wyoming Province showing variations in levels of thermal maturity based on vitrinite reflectance (R_o) for the Niobrara Formation and equivalent rocks.

were generated for three wells to model petroleum-generation history of Niobrara source rocks. The Texas Pacific #1 Bear, located along the shallow southeastern flank of the Sand Wash Basin (fig. 7), is located in sec. 26, T. 7 N., R. 89 W. The Koch Exploration #1 Adobe Town unit, located in the deep central part of the Washakie Basin (fig. 7), is in sec. 20, T. 15 N., R. 97 W. The Southland Royalty #1 Eagles Nest, located in the deep northern part of the Great Divide Basin (fig. 7), is located in sec. 29, T. 25 N., R. 91 W. Two types of modeling were performed on these wells to predict timing and type of hydrocarbon generation. They are (1) time-temperature modeling based on vitrinite reflectance and (2) kinetic modeling based on time-temperature integrated with the results of hydrous-pyrolysis experiments.

Time-temperature modeling predicts critical levels of thermal maturity based on vitrinite reflectance by integrating burial and thermal history and time (fig. 11). The burial-history curve for the #1 Bear well (fig. 11a) indicates that the base of the Niobrara was buried to a depth of approximately 7,500 ft and entered the oil window at about 72 Ma. The top of the Niobrara passed through the oil window at maximum burial of 12,500 ft and entered the oil cracking phase, which ended when regional uplift and cooling occurred at about 5 Ma. The burial-history curve for the #1 Adobe Town well (fig. 11b) shows that the Niobrara was buried to a depth of about 9,000 ft when entering the oil window at 71 Ma. With continued subsidence and the accumulation of about 6,500 ft of additional sediment along the deep axis of the Washakie Basin, the Niobrara passed through the oil window at 57 Ma and reached an R_o of 1.35 percent, the level of thermal maturity generally considered sufficient to crack oil to gas. The burial-history curve for the #1 Eagles Nest well (fig. 11c) shows a burial history similar to the #1 Adobe Town well. In this well the Niobrara was buried to about 11,000 ft and entered the oil window at about 67 Ma. With additional accumulation of 7,500 ft of sediments in the deep trough of the Great Divide Basin, the Niobrara passed through the oil window by 56 Ma, when the thermal cracking of oil to gas was then initiated.

Kinetic models were also generated for these same wells and used to reconstruct the maturation history of Type-II oil-prone kerogen (fig. 12). Kinetic modeling by Roberts and others (Chapter 3, this CD–ROM) uses time and temperature integrated with results of laboratory hydrous-pyrolysis experiments to predict timing and type of hydrocarbon generation. Modeling by Roberts and others (this CD–ROM) using hydrous-pyrolysis kinetic parameters of Lewan and Ruble (2002) suggests that oil generation for Type-II kerogen begins at an R_o of 0.68–0.69 percent, peaks at around 0.92 percent, and ends at an R_o of 1.13 to 1.17 percent. The bottom of the oil window occurs at a transformation ratio of 0.99, meaning there is essentially no kerogen left to convert to oil.

The level of thermal maturity at which oil is cracked to gas is uncertain but is generally thought to be greater than an R_o of about 1.35 percent (Law, 2002); however, hydrous-pyrolysis experiments by Tsuzuki and others (1999) indicate that oil is stable at higher maturities. The results of modeling by Roberts and others (Chapter 3, this CD–ROM) using hydrous-pyrolysis kinetic parameters of Tsuzuki and others (1999) indicate that oil cracking begins at an R_o of about 1.72 percent, gas generation peaks at around 2.39 percent and ends around 2.79 percent. The end of the gas-generation phase occurs at a transformation ratio of 0.99, meaning there is virtually a 100-percent reaction and almost no oil left to transform to gas.

Based on the hydrous-pyrolysis kinetic models, timing of oil generation in the #1 Bear (fig. 12a) well shows that the Niobrara began generating oil at about 70 Ma, remained in the oil window until about 43 Ma, but did not reach thermal maturities sufficient to crack oil to gas. Oil generation began in the 1 Adobe Town well (fig. 12b) around 68 Ma and ended by 60 Ma. Continued burial in the deeper part of the Washakie Basin elevated maturities to a level sufficient to crack oil to gas at around 54 Ma, and with additional burial the Niobrara passed through the gas window by 48 Ma. Oil generation in the #1 Eagles Nest well (fig. 12c) began at 66 Ma and ended by 59 Ma. Gas generation from thermal cracking of oil began around 54 Ma and continued until about 24 Ma.

Migration Summary

Landon and others (2001) believe that given the fine-grained lithology, low matrix porosity and permeability of the Niobrara, and the integrity of the overlying and interbedded seals, hydrocarbons have not migrated far from where they were generated. Figure 10 shows that most of the oil production from the Niobrara in the SWWP is in areas where the Niobrara is thermally mature with respect to oil generation (0.60 percent to 1.35 percent R_o), with few wells producing in areas where the Niobrara is immature or marginally mature (R_o<0.60 percent). This relationship of thermal maturity and hydrocarbon production also indicates that most of the oil that has been produced was generated in place and has not migrated great distances into less mature reservoirs.

Events Chart

The events chart (fig. 13) summarizes the essential elements of source rock, reservoir rock, seal rock, and overburden rock and the processes of generation, migration, accumulation, and trap formation that are essential to form petroleum accumulations. Deposition of source, reservoir, and intraformational seal rocks of the Niobrara Formation in the SWWP occurred during Late Cretaceous time (88–84 Ma). This was followed by deposition of several thousand feet of Mancos Shale, and equivalent Steele Shale, forming a thick, overlying regional seal. Based on burial-history and petroleum-generation curves, the amount of overburden rock required to reach thermal maturation levels sufficient to gener-

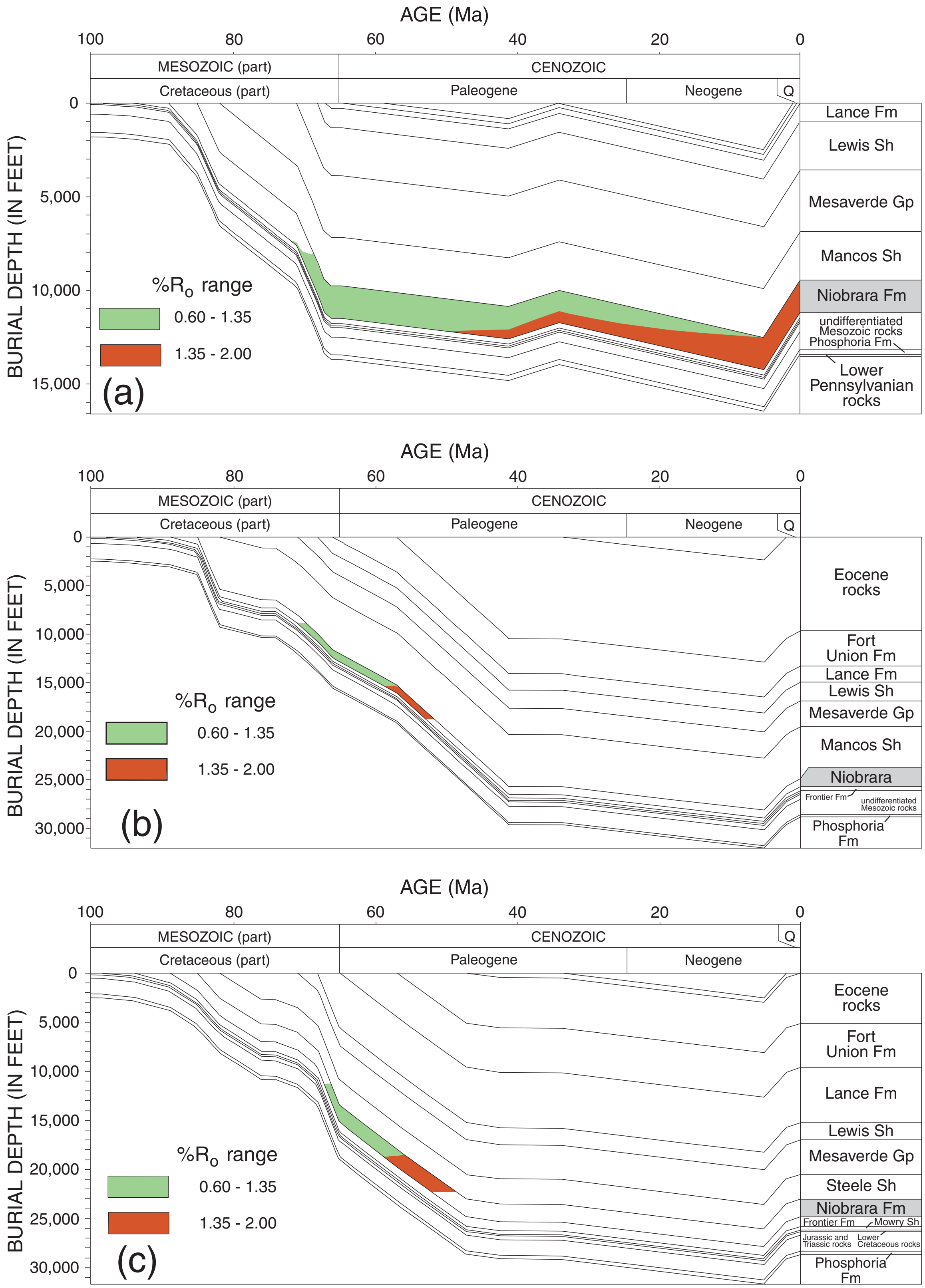

Figure 11. Burial-history curves showing levels of thermal maturity based on vitrinite reflectance for the (a) Texas Pacific #1 Bear, (b) Koch Exploration #1 Adobe Town, and (c) Southland Royalty #1 Eagles Nest. Location of wells is shown in figure 7. Burial-history curves were constructed using the program PetroMod1D Express (version 1.1).

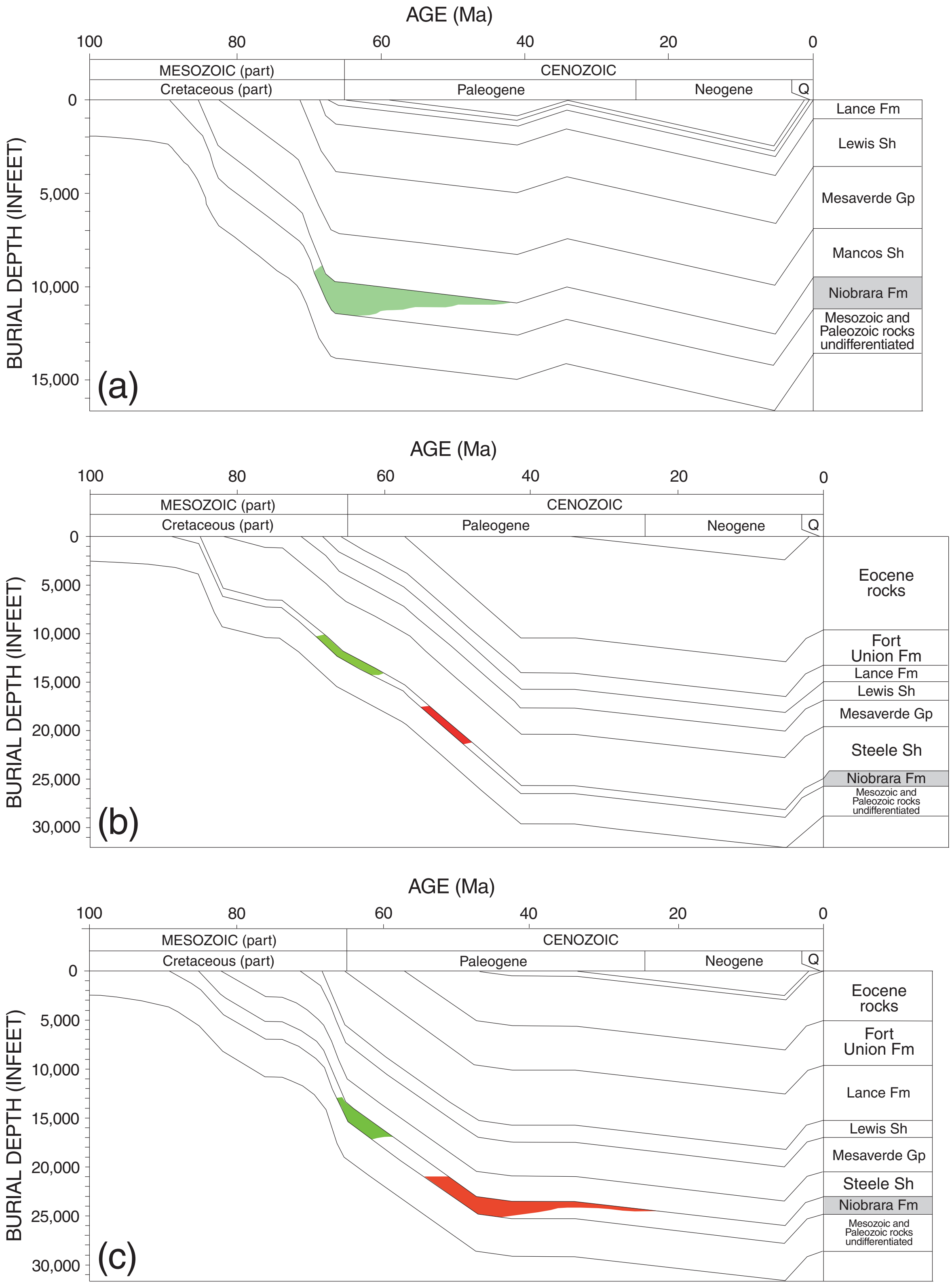

Figure 12. Burial-history curves showing maturation history of Type-II kerogen based on hydrous-pyrolysis kinetic models for the (a) Texas Pacific #1 Bear, (b) Koch Exploration #1 Adobe Town, and (c) Southland Royalty #1 Eagles Nest. Location of wells is shown in figure 7. Burial-history curves were constructed using the program PetroMod1D Express (version 1.1). Green represents the oil window. Red represents the gas-generation phase from the thermal cracking of oil.

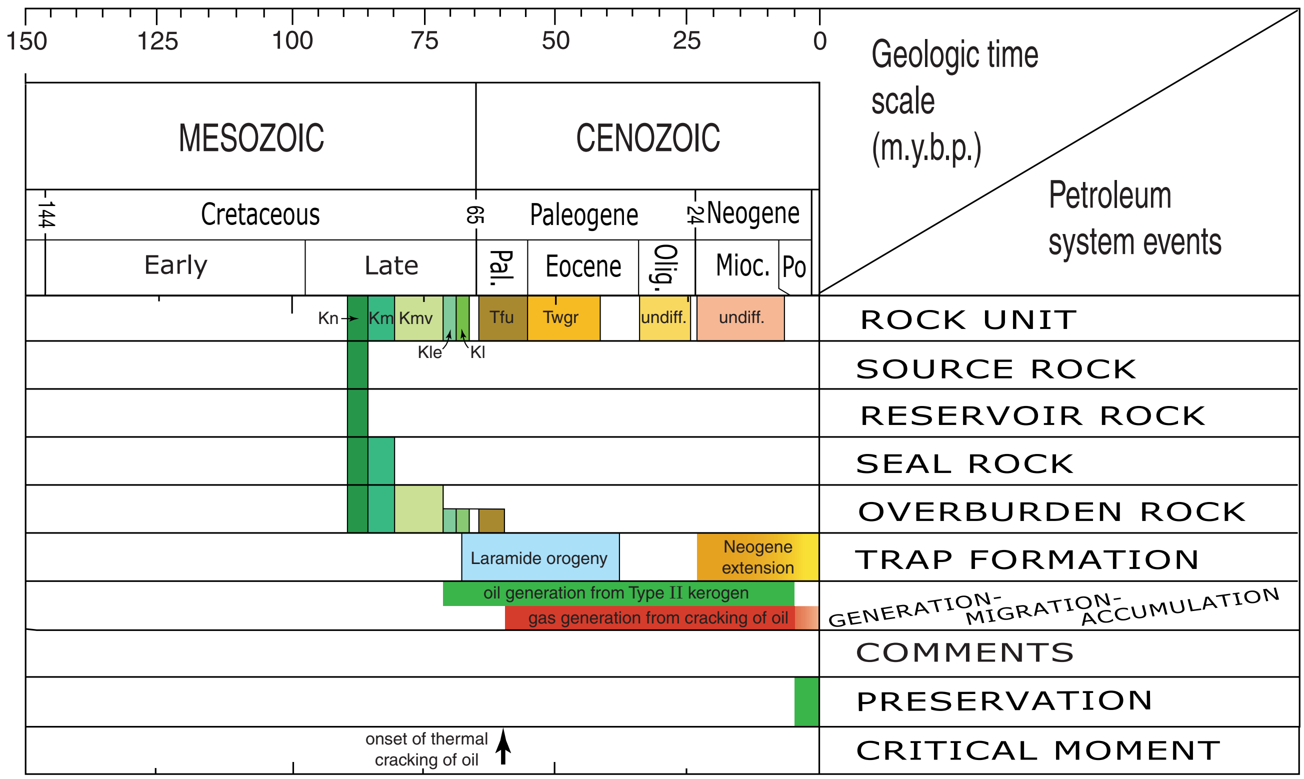

Figure 13. Events chart showing the relationship of essential geological elements and processes for the Niobrara Total Petroleum System and assessment units. Kn, Niobrara Formation; Km, Mancos or Steele Shale; Kmv, Mesaverde Group; Kle, Lewis Shale; Kl, Lance Formation; Tfu, Fort Union Formation; Twgr, Wasatch and Green River Formations; undiff., undifferentiated Oligocene or Miocene deposits.

ate oil occurred at about 72 Ma. Critical overburden deposition was from the Mancos Shale and equivalent rocks and several thousand feet of the Mesaverde Group. Along the shallow flanks of the basin, the Niobrara remained in the oil window until about 10–5 Ma when regional uplift and erosion occurred (preservation time). With continued subsidence and the additional accumulation of 6,500 to 7,500 ft of sediments of the Lewis Shale, Lance Formation, and the Fort Union Formation in the deeper parts of the basin, the Niobrara passed through the oil window at approximately 59 Ma, reaching thermal maturities greater than 1.35 percent R_o and initiating thermal cracking of oil to gas (critical moment). Because mainly oil is produced from Niobrara reservoirs that are thermally mature with respect to oil (R_o 0.60 to 1.35 percent) and Niobrara-sourced oil is not found in other reservoir rocks, it appears that little or no migration has taken place. Fractures that form the reservoirs in brittle, calcareous-rich zones of the Niobrara developed as a result of Laramide compressional tectonics, and during post-Laramide Neogene extension. These fractured carbonate-rock reservoirs are associated with anticlinal, synclinal, and monoclinal folds, and fault zones.

Assessment Units in the Niobrara Total Petroleum System (503703)

An assessment unit (AU) is a mappable volume of rock within a Total Petroleum System that contains known or postulated oil and gas accumulations that share similar geologic characteristics (Klett and others, 2000). The Niobrara Total Petroleum System (503703) is subdivided into two AUs based on levels of thermal maturity: (1) a continuous oil assessment unit (AU 50370361), and (2) a continuous gas assessment unit (AU 50370362).

Niobrara Continuous Oil Assessment Unit (AU 50370361)

The Niobrara Continuous Oil Assessment Unit (AU 50370361) is an established AU that produces mainly oil from self-sourced, organic-rich fractured carbonate-rock reservoirs. It encompasses approximately 4,600 mi^2 and occupies the southern and eastern flanks of the Sand Wash Basin in Colorado and the eastern flanks of the Washakie and Great Divide Basins in Wyoming (fig. 14). The eastern boundary of the

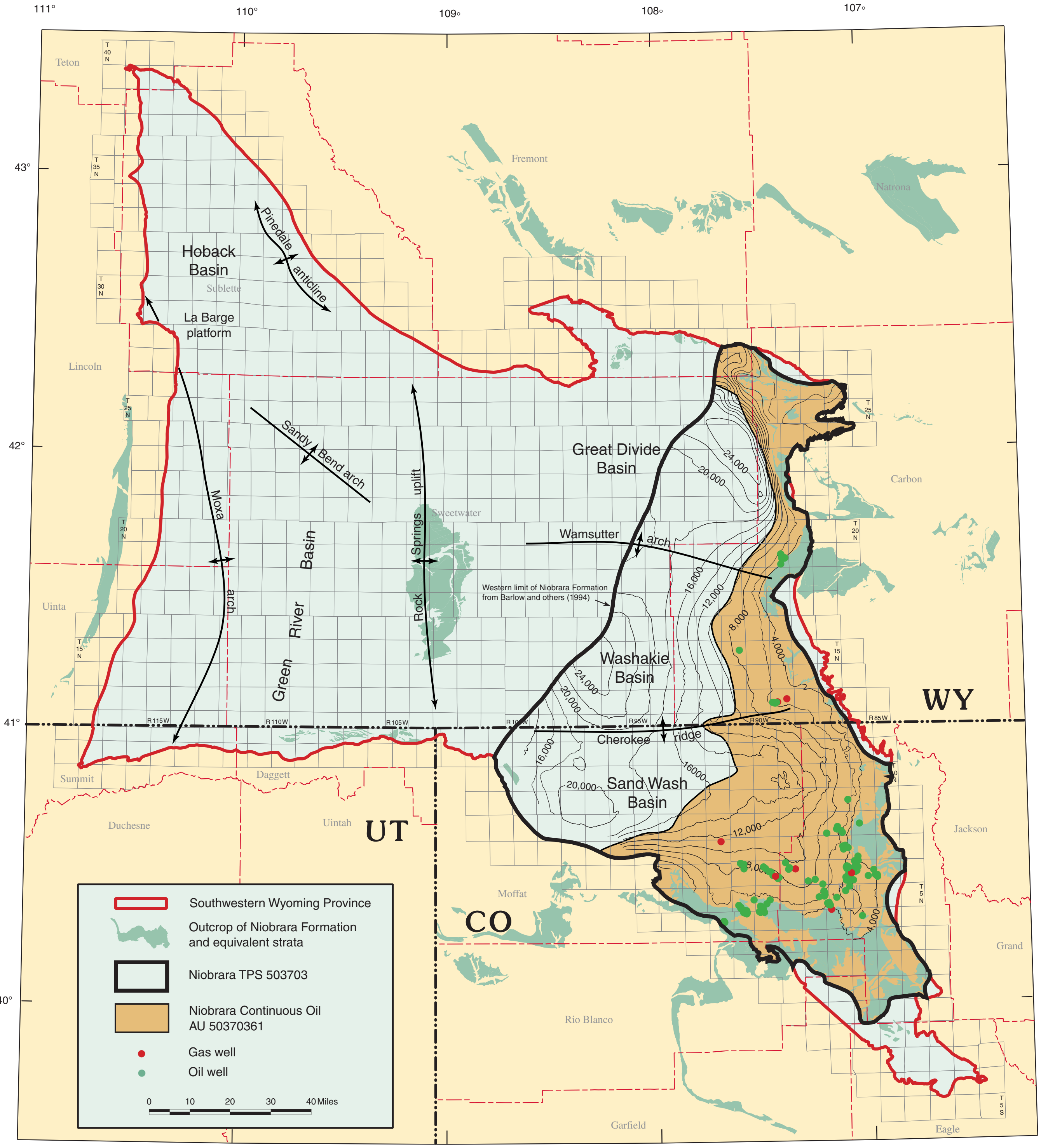

Figure 14. Southwestern Wyoming Province showing the areal extent of the Niobrara Continuous Oil Assessment Unit (AU 50370361) and location of producing wells. Contours show approximate depth to the base of the Niobrara Formation (modified from Kirschbaum and Roberts, Chapter 5, this CD–ROM). Contour interval = 2,000 feet.

Continuous Oil AU, coinciding with the TPS boundary, is the base of the outcrop of the Niobrara Formation or stratigraphic equivalent strata at the base of the Mancos or Steele Shales; the southern boundary is the Axial Basin uplift (fig. 1). The western boundary is defined by the 1.35 percent R_o contour, which is generally considered the bottom of the oil window and the level of thermal maturity at which oil cracks to gas (Law, 2002; Hunt, 1996). This AU is restricted stratigraphically to the Niobrara and equivalent rocks because there is no geochemical evidence of Niobrara-type oils being produced from other reservoir rocks, indicating little or no migration has taken place. This is due to the presence of overlying and interbedded thick plastic shales that seal fractured Niobrara reservoirs and provide a barrier to migration.

The oil accumulations in the Niobrara and equivalent strata are of the continuous type (unconventional) using the criteria established by Schmoker (1996) and have the following characteristics:

1. Lack of downdip water contacts (Vincelette and Foster, 1992; Mallory, 1977).
2. Little or no water production (Vincelette and Foster, 1992; Cummings, 1961).
3. Production extending downdip off structure into synclinal areas (Vincelette and Foster, 1992).
4. Abnormally pressured (either high or low). Vincelette and Foster (1992) report a pressure gradient for the Buck Peak field of 0.285 psi/ft calculated from drill-stem tests. Unpublished pressure data reports pressure gradients for fields in the Sand Wash Basin range from 0.25 to nearly 0.40 pounds per square inch per foot (P.H. Nelson and J. Kibler, U.S. Geological Survey, oral commun., 2003).
5. Production independent of structural closure (Vincelette and Foster, 1992; Mallory, 1977).
6. Reservoirs in close association with source rocks.

The Niobrara Continuous Oil Assessment Unit is lightly explored with the first oil discovery at Tow Creek in 1924 (Ogle, 1961). Since then, according to the IHS Energy Group (2001) production database, 337 wells have penetrated the Niobrara section, with approximately 150 producing from the Niobrara. Producing intervals range in depth from 1,200 to nearly 10,000 ft. According to Vincelette and Foster (1992), most production to date is associated with the Laramide-age anticlinal and monoclinal folds (fig. 9), and many of these accumulations (“sweet spots”) were discovered while drilling known structures for deeper conventional reservoir horizons. Due to the underpressured nature of the Niobrara reservoirs, it is suggested that many potential producers were bypassed because conventional drilling muds may have caused formation damage or masked shows in the Niobrara. Potential for future discoveries in this oil AU would most likely be “sweet spots” formed by fractures associated with Laramide compressional features, including faults, anticlinal and synclinal trends, regional lineament features, and faulting associated with post-Laramide Neogene extension.

Niobrara Continuous Gas Assessment Unit (AU 50370362)

The Niobrara Continuous Gas Assessment Unit (AU 50370362) is a hypothetical assessment unit that is believed to have the potential to produce natural gas from fractured carbonate-rich reservoirs in the Niobrara Formation and equivalent rocks. The gas is self-sourced and believed to have originated from the thermal cracking of self-sourced oil within the Niobrara Formation. The gas AU encompasses approximately 3,800 mi^2 of the western half of the Niobrara TPS and is located in the deeper downdip parts of the Sand Wash, Washakie, and Great Divide Basins (fig. 15). The eastern boundary of the gas AU is defined by the 1.35 percent R_o contour, the level of thermal maturity that is commonly believed to be the bottom of the oil window and the level at which oil begins to thermally crack to gas (Law, 2002; Hunt, 1996). The southern boundary of the gas AU is defined by the Axial Basin uplift (fig. 1). The western boundary of the AU is the western limit of the Niobrara facies in the subsurface as mapped by Barlow and others (1994) and coincides with the western boundary of the Niobrara TPS. Good-quality top seals are provided by the soft plastic shales of the overlying Mancos and Steele Shales that act as a barrier for vertical migration; thus, the gas AU is restricted stratigraphically to the Niobrara interval.

The Niobrara Continuous Gas Assessment Unit (AU 50370362) is characterized as a continuous-type (unconventional) accumulation with the characteristics of an indirect basin-centered gas system (BCGS) as defined by Law (2000, 2002). Some of the characteristics of the Niobrara Continuous Gas Assessment unit that are attributes of an indirect BCGS include:

1. Oil-prone source rock.
2. Pressure mechanism – oil cracking.
3. Top of BCGS greater than 1.3–1.4 percent R_o.
4. Abnormally pressured. Reservoir pressures reported for the Twin Buttes field in the northern part of the Great Divide Basin indicate a pressure gradient for the Niobrara reservoir of 0.28 psi/ft (Kendell, 1979).
5. Good quality top seal.

Little exploration has taken place within this gas AU because throughout most of the AU the top of the Niobrara

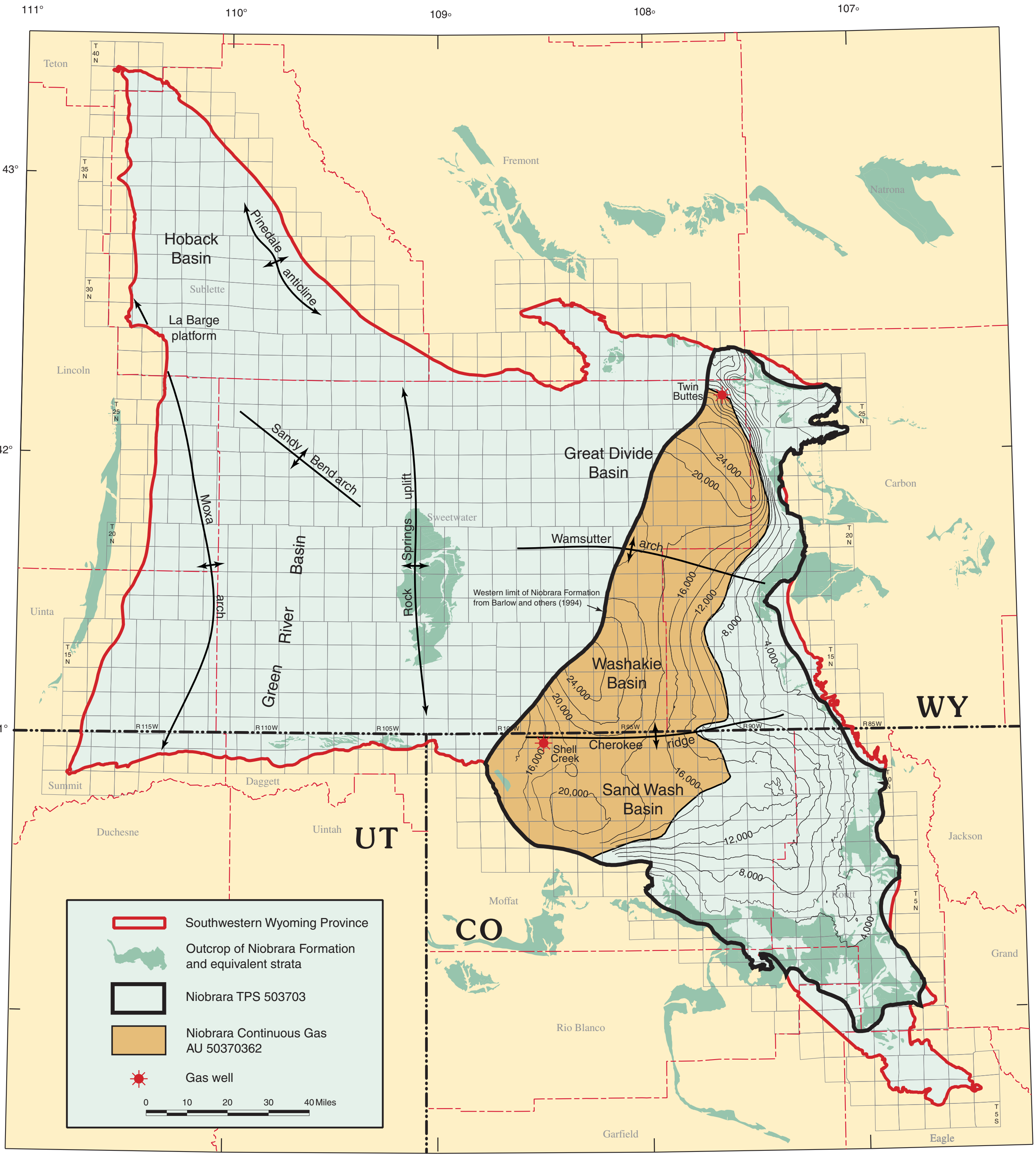

Figure 15. Southwestern Wyoming Province showing the areal extent of the Niobrara Continuous Gas Assessment Unit (AU 5037062) and location of producing wells. Contours show approximate depth to the base of the Niobrara Formation (modified from Kirschbaum and Roberts, Chapter 5, this CD–ROM). Contour interval = 2,000 feet.

occurs at depths ranging from 12,000 to greater than 22,000 ft in the deep troughs of the Sand Wash, Washakie, and Great Divide Basins (fig. 15). According to IHS Energy Group (2001) database, only two fields produce or have produced natural gas from single wells in the Niobrara or equivalent strata: (1) the Twin Buttes field located in the northern part of the Great Divide Basin, and (2) the Shell Creek field located along the southern flank of the Cherokee ridge (fig. 15). During the late 1970s, the Twin Buttes field produced natural gas from what is now a single shut-in well in the Niobrara at depths greater than 13,000 ft. Cumulative production in this well was nearly 11 MMCF with no oil or water production reported. The Shell Creek field currently produces natural gas from a single well in the Niobrara at depths greater than 15,000 ft, with a cumulative production through 1999 of approximately 226 MMCF, 3,694 barrels of water, and no oil. Potential for future discoveries in this AU would most likely be "sweet spots" associated with fracture development located along major structural elements such as the Cherokee ridge and the Wamsutter arch.

Assessment Results of Undiscovered Resources

Niobrara Continuous Oil Assessment Unit (AU 50370361)

The Niobrara Continuous Oil Assessment Unit (AU 50370361) covers approximately 4,600 mi^2 in the eastern portion of the SWWP (fig. 14). Input data for the assessment are shown on the FORSPAN ASSESSMENT MODEL FORM in the Appendix. The minimum, median, and maximum areas, in acres, for the AU are 2,622,000, 2,914,000, and 3,205,000 acres, respectively. The reason for the uncertainty is because the position of the 1.35-percent R_o isotherm, the western boundary of the AU, is based on sparse R_o data. The AU is mostly untested with only 337 wells penetrating the Niobrara section for a median percentage of 2 percent of the total AU area tested. Of the 337 tested cells, 133 were identified as producers for a historical success ratio of 40 percent. This success ratio might have possibly been higher, but due to the underpressured nature of the Niobrara reservoirs it is believed that many potential producers were bypassed because conventional drilling muds may have caused formation damage or masked shows in the Niobrara.

The minimum, median, and maximum percentages of the untested AU area that has potential for additions to reserves in the next 30 years are 2, 5, and 8 percent, respectively (see Appendix). The median area represents potential fracture ("sweet spots") development associated with known anticlinal and synclinal trends, faults and fault zones, and plunges of folds, identified from published geologic and structure maps (Love and Christiansen 1985; Tweto, 1976, 1979; Barlow and Haun, Inc., 1997). These areas would most likely occur in areas where thermal maturities range from 0.60 to 1.35 percent R_o. The maximum area would include additional unidentified subtle structures and regional lineaments (Maughan and Perry, 1986; Thomas, 1971). The minimum area accounts for fractures that contain vein-filling minerals, thus resulting in a loss of permeability and nonproductive reservoirs (Vincelette and Foster, 1992).

Graphs showing the estimated ultimate recovery (EUR) distribution for Niobrara wells are shown in figure 16. Figure 16a shows the distribution for all wells, and figure 16b shows the distribution by discovery thirds. The number of wells in each discovery third is the same, but the time span represented for each third may be different. The median EUR for all wells is 55,000 barrels of oil (BO) with a maximum of 1,600,000 BO. Median EURs for the first, second and third discovery thirds are 150,000, 60,000, and 20,000 BO (Appendix), respectively. Lower EURs for the second and third thirds most likely reflects interference among infill wells drilled at closer than optimal spacing.

The minimum, median, and maximum total recovery per cell for untested cells having potential for additions to reserves over the next 30 years is 1,000 BO, 80,000 BO, and 1,600,000 BO, respectively (Appendix). The median of 80,000 BO is lower than that of the historical first third of 150,000 BO because we suggest that many of the best locations were drilled early, but is higher than the median for the second and third discovery thirds because we believe that if new wells are drilled outside areas of established production,they will not experience interference problems.

The minimum, median, and maximum area per cell of untested cells having the potential for additions to reserves in the next 30 years is 40, 160, and 400 acres, respectively. This wide range in drainage areas reflects the variable production that can be typical of many fractured reservoirs. Variable production in these wells is due to the rapid lateral changes in fracture intensity caused by lithologic variations, fault intensity, and tectonic setting (Vincelette and Foster, 1992).

Tabulated results for the Niobrara Continuous Oil Assessment Unit for undiscovered oil, gas, and natural gas liquids that have potential for additions to reserves in the next 30 years are summarized in table 1.

Niobrara Continuous Gas Assessment Unit (AU 50370362)

The Niobrara Continuous Gas Assessment Unit (AU 50370362) was not quantitatively assessed because of the lack of production data or a suitable analog.

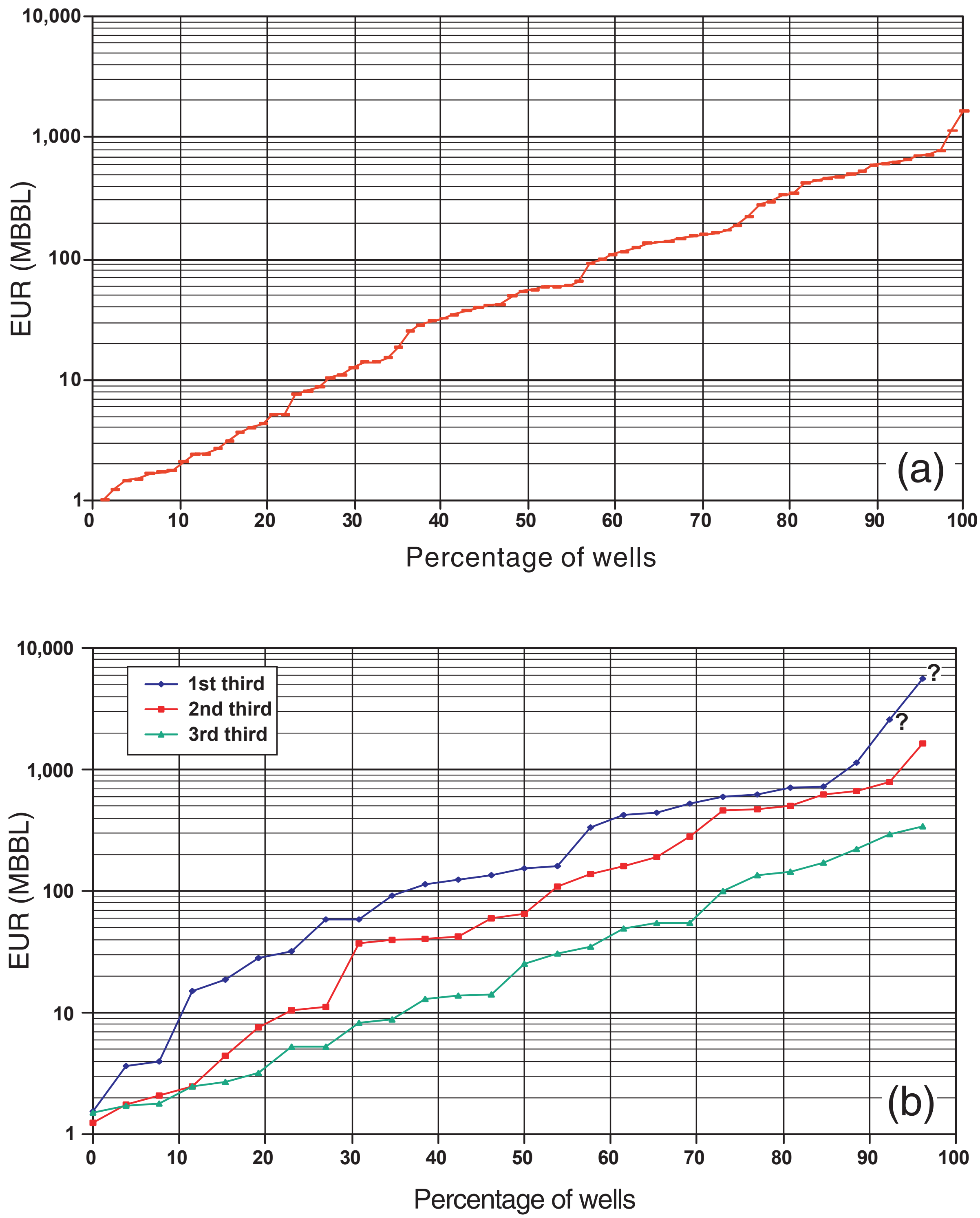

Figure 16. Estimated ultimate recovery (EUR) for wells in the Niobrara Continuous Oil Assessment Unit (AU 50370361): (a) EUR distribution for all wells, (b) EUR distribution by discovery thirds. Discovery thirds refers to the division into three equal parts of the number of wells drilled in the AU. The wells were ordered by completion date and then divided into three equal or nearly equal numbers of wells in order to investigate how the EURs have changed with time. The 2.5 and 5.5 MMBBL points indicated by a (?) on the curve for the 1st discovery third are most likely multiple wells listed under a single lease name and probably do not represent EURs for a single well.

Table 1. Summary of assessment results for the Niobrara 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. 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
Niobrara TPS													
Niobrara Continuous Oil AU	***Oil***	66.90	100.50	151.00	103.60	34.90	59.10	99.90	62.20	1.90	3.50	6.50	3.70
	Gas					0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Niobrara Continuous Gas AU	***Gas***	Not quantitatively assessed											
Total continuous resources		**66.90**	**100.50**	**151.00**	**103.60**	**34.90**	**59.10**	**99.90**	**62.20**	**1.90**	**3.50**	**6.50**	**3.70**

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Appendix A. Data form used for evaluating the Niobrara Continuous Oil Assessment Unit, Niobrara Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah.

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

IDENTIFICATION INFORMATION

Assessment Geologist:…	T.M. Finn and R.C. Johnson	Date:	8/26/2002
Region:……………………	North America	Number:	5
Province:………………….	Southwestern Wyoming	Number:	5037
Total Petroleum System:.	Niobrara	Number:	503703
Assessment Unit:……….	Niobrara Continuous Oil	Number:	50370361
Based on Data as of:……	IHS Energy Group, 2001, NRG 2001 (data current through 1999), Wyoming Oil and Gas Conservation Commission		
Notes from Assessor…..			

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-Unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo) Oil
What is the minimum total recovery per cell?… 0.001 (mmbo for oil A.U.; bcfg for gas A.U.)
Number of tested cells:………… 337
Number of tested cells with total recovery per cell ≥ minimum: ……... 133
Established (>24 cells ≥ min.) X Frontier (1-24 cells) ____ Hypothetical (no cells) ____
Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)
1st 3rd discovered 0.15 2nd 3rd 0.06 3rd 3rd 0.02

Assessment-Unit Probabilities:

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

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

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

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

1. Total assessment-unit area (acres): (uncertainty of a fixed value)
minimum 2,622,000 median 2,914,000 maximum 3,205,000

2. Area per cell of untested cells having potential for additions to reserves in next 30 years (acres):
(values are inherently variable)
calculated mean 173 minimum 40 median 160 maximum 400

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)
minimum 97 median 98 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 2 median 5 maximum 8

Appendix A. Data form used for evaluating the Niobrara Continuous Oil Assessment Unit, Niobrara Total Petroleum System, Southwestern Wyoming Province, Wyoming, Colorado, and Utah.—Continued

Assessment Unit (name, no.)
Niobrara Continuous Oil, Assessment Unit 50370361

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 0.001 median 0.08 maximum 1.6

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)………………………..…….	300	600	900
NGL/gas ratio (bngl/mmcfg)……………………..….	30	60	90
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)……………..……			

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

Oil assessment unit:	minimum	median	maximum
API gravity of oil (degrees)…………….………..	35	39	45
Sulfur content of oil (%)…………………….…..…	0.02	0.1	0.5
Drilling depth (m) ……………...……………..……	610	1500	2750
Depth (m) of water (if applicable)………………			
Gas assessment unit:			
Inert-gas content (%)………………………...…...			
CO_2 content (%)……………………………..…...			
Hydrogen-sulfide content (%)…………...………			
Drilling depth (m)………………………………….			
Depth (m) of water (if applicable)………………			

Success ratios:	calculated mean	minimum	median	maximum
Future success ratio (%)..	60	50	60	70

Historical success ratio, tested cells (%) 40

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